Selective NOx Recirculation for Lean Burn Natural Gas Engines

DOE Sponsors
Ronald Fiskum, Program Sponsor, DOE/EERE
William Cary Smith, Project Manager, DOE/NETL
Raj Sekar, Technical Manager, ANL

WVU Project Team
Nigel Clark, Gregory Thompson, Chamila Tissera, Emre Tatli, Andy Zimmerman, Richard Atkinson, Jaykumar Vidiyanadan

Industry Interaction
Sorbent Technologies (Twinsburg, Ohio)
Cummins, Inc. (Columbus, Indiana)

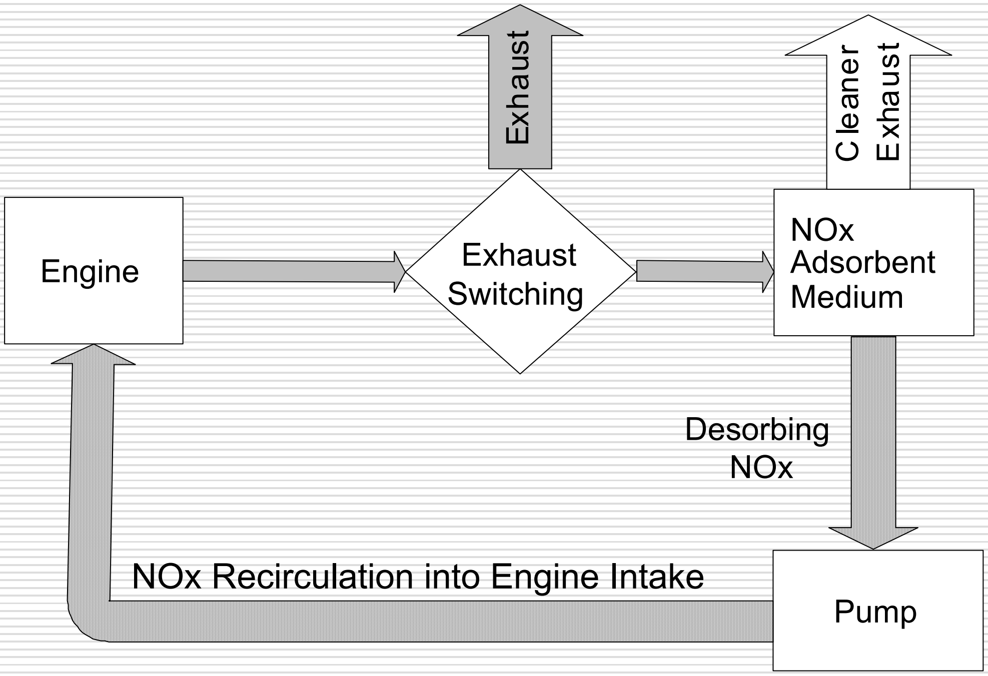
COOPERATIVE AGREEMENT: DE-FC26-02NT41608

National Research Center for Alternative Fuels, Engines & Emissions

West Virginia University

Selective NOx Recirculation (SNR)

- Basic Steps
  - Adsorption of NO_X
  - Periodic desorption of NO_X
  - Recirculation of NO_X into the combustion chamber
  - Concept promoted by Sorbent Technologies
  - Prior papers by (Krutzsch et al., 1998 and (Chaize, E. et al., 1998)



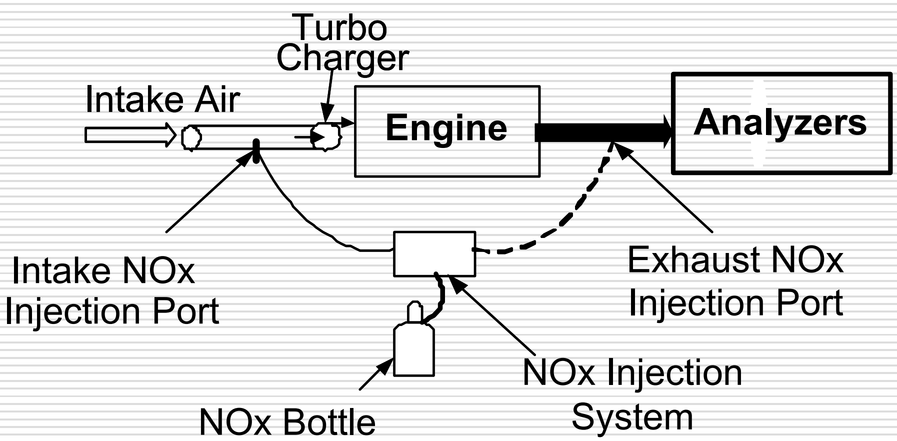
Benefits

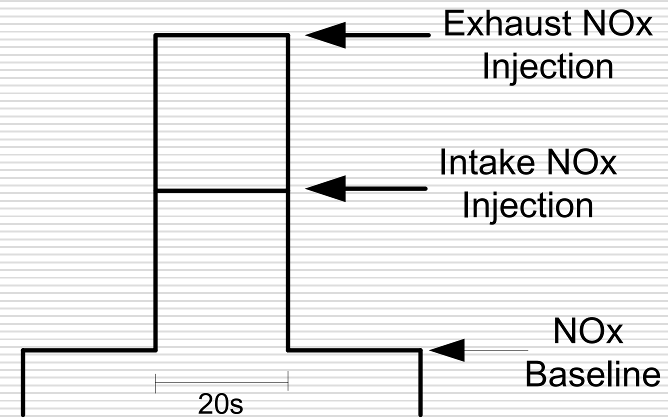
- Employs established components
- Eliminates consumable reductants
- Minimizes engine modifications

Outline

- NOx decomposition in a lean burn natural gas engine
- Chemical kinetic modeling of NOx decomposition
- NOx decomposition on a stoichiometric/rich burn natural gas engine
- Use of EGR with stoichiometric/rich burn operation
- System modeling prediction
- Preliminary NOx adsorber characteristics
- Timeline and future plans

Establishing NO_X Decomposition Rates





- Nitric oxide (NO) 98.8% purity was injected
- NOx Decomposition percentage was quantified by comparing 20-second injections made into the exhaust vs. intake
- Peak value is for central averaged 10 seconds of injection
- NOx decomposition % = $1-\frac{\left(NO_{X\_Peak\_Intake}-NO_{X\_Baseline}\right)}{\left(NO_{X\_Peak\_Exhaust}-NO_{X\_Baseline}\right)}$

Initial Characterization of NOx Decomposition (Test Engine – 1)

- 1993 Cummins L10 240G
- Lean-burn natural gas engine
- Inline 6 cylinder
- Spark ignited
- Turbocharged
- Open-loop fuel mixer

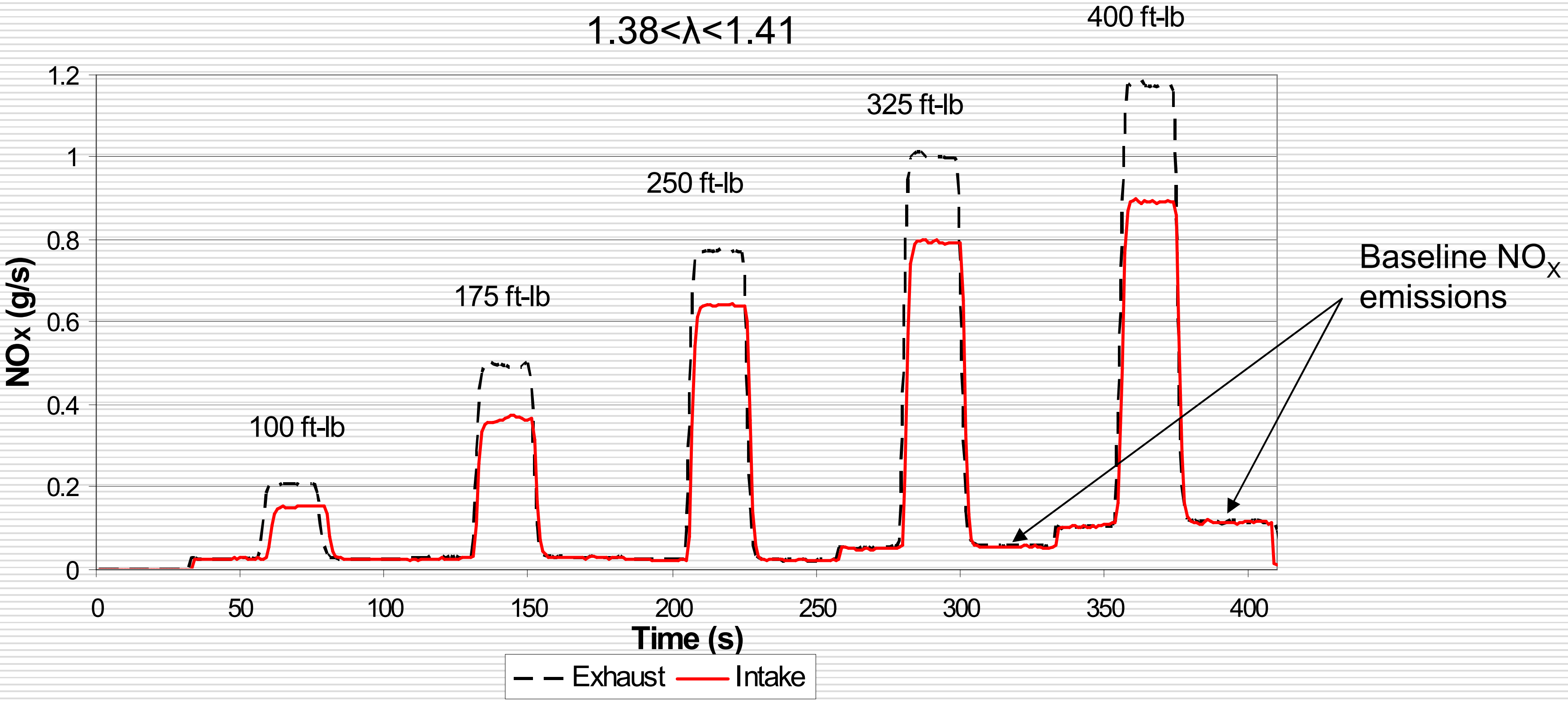
1993 Cummins L10G Controlled Variables

Test Engine	Load (ft-lb)	Speed (rpm)	Injected NOx(%)	Air/Fuel Ratio (λ)
Cummins L10G	Varied 100-400	Constant 800	Varied 0.5 - 2.5	Varied 1.35-1.41

Sample NOx Injection Matrix

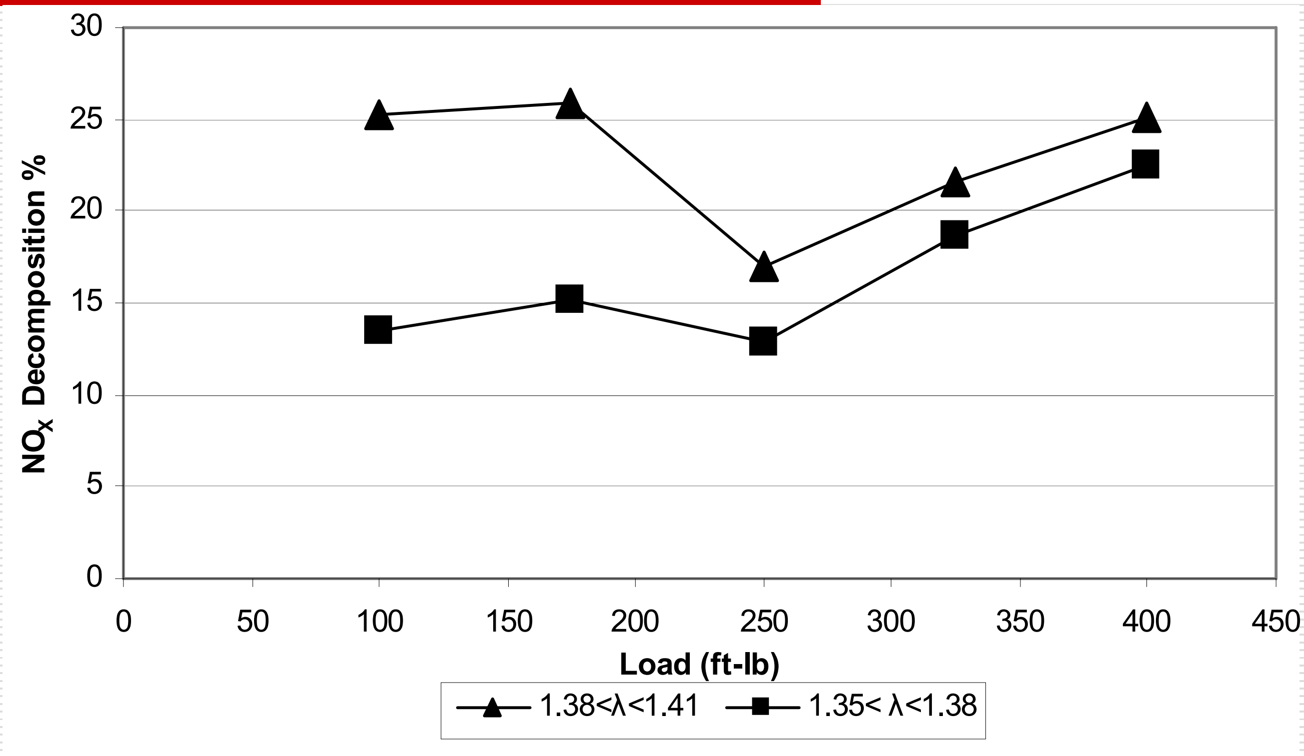
Speed (rpm)	Load (ft-lb)	NOx% in Intake	Intake Flow Rate (lps)
800	100	2.5	21
800	175	2.5	36
800	250	2.5	47
800	325	2.5	57
800	400	2.5	64

1993 Cummins L10G - NOx Injections at Increasing Load



- Injections made at each load change 100 to 400 ft-lb for lambda 1.38<λ<1.41
- The same test was conducted with a "less lean" lambda of 1.35<λ<1.38

1993 Cummins L10G - Effects of Load and Air/Fuel Ratio

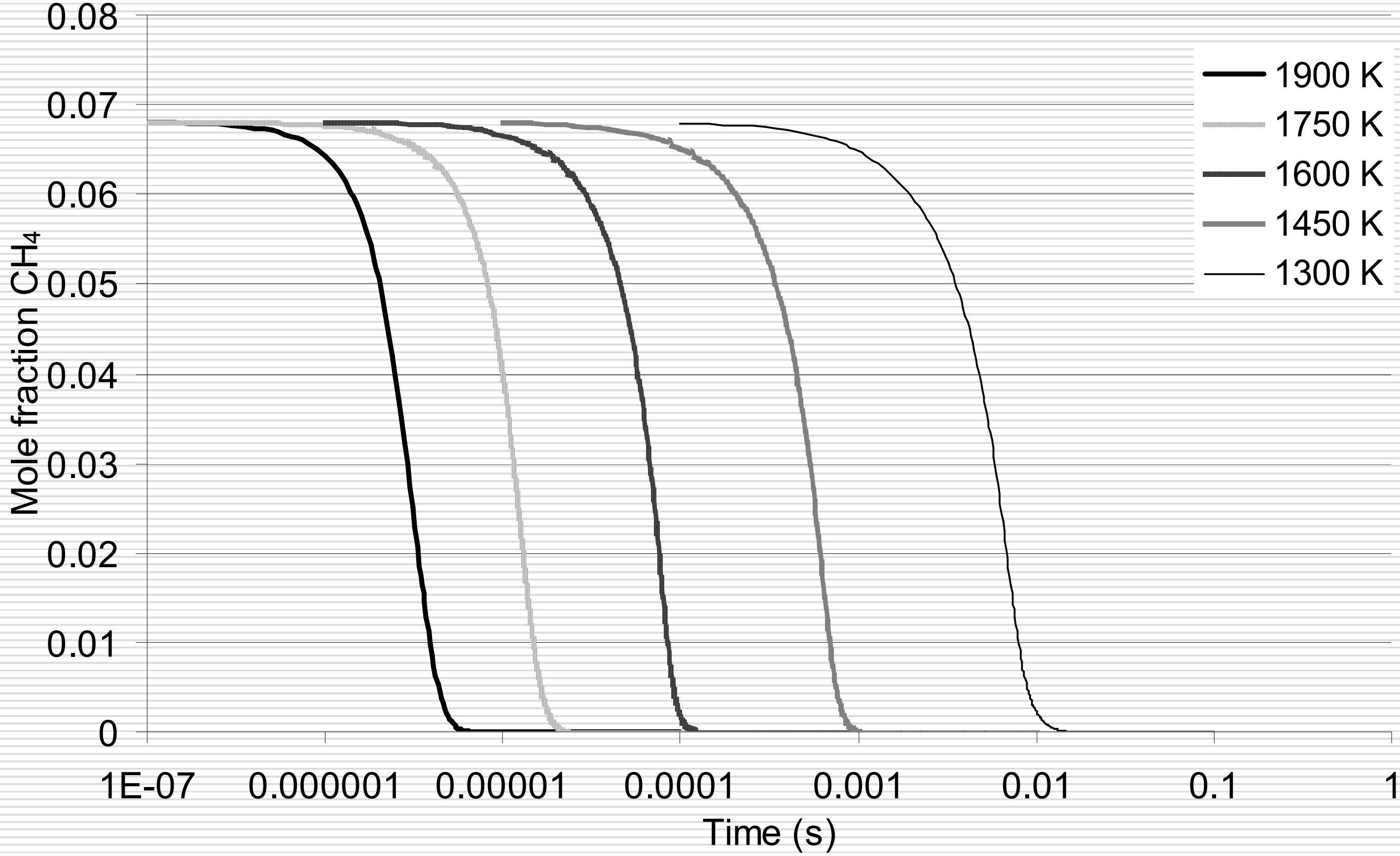


- Slight change in air/fuel affected on NO_X decomposition
- Data published in ASME ICED2004-839 and SAE 2005-01-0234
- NOx decomposition levels insufficient for practical application

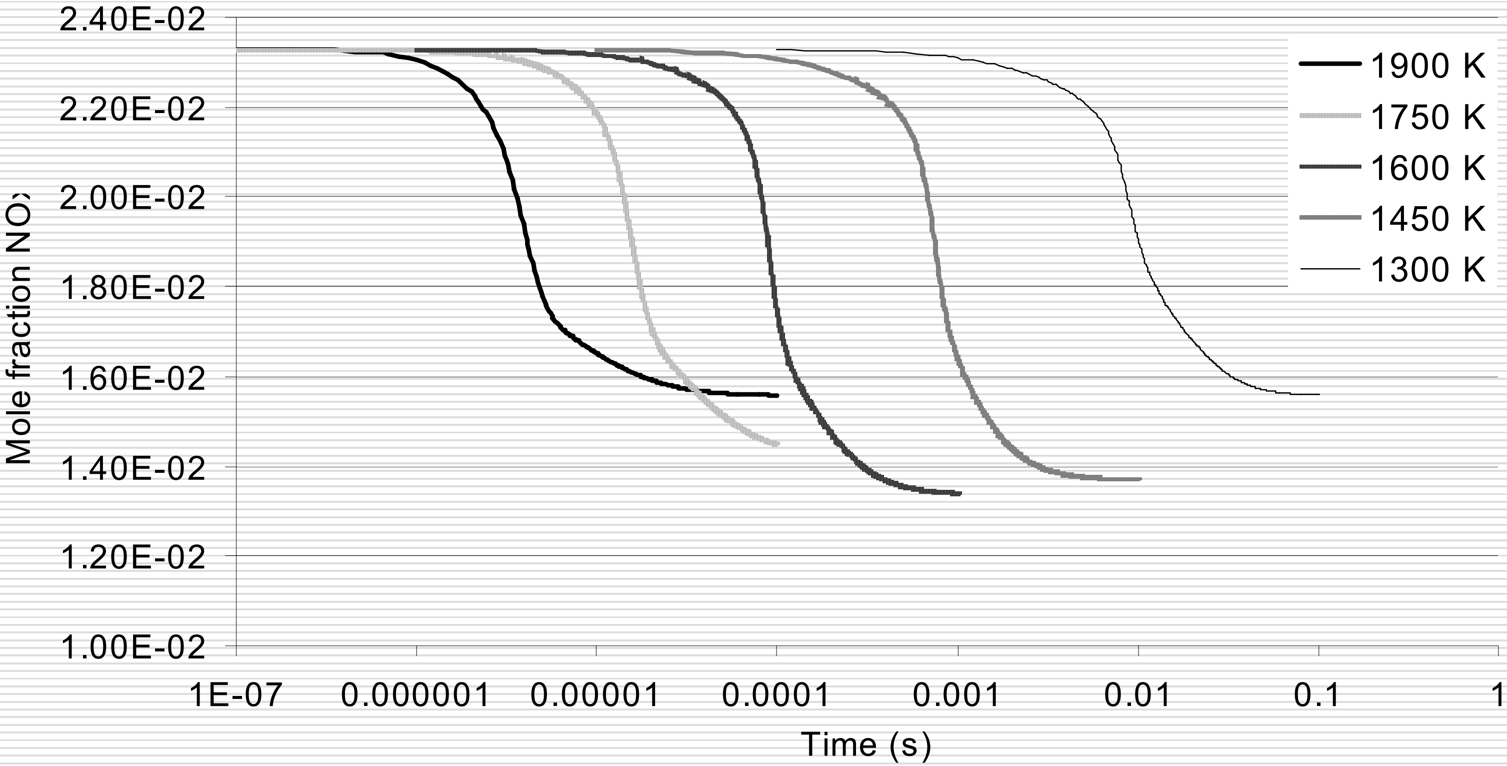
Chemical Kinetic Modeling for a Natural Gas Engine

- Intent was to find suitable operating conditions for high decomposition
- Chemical kinetic modeling used CHEMKIN 4.0 software from Reaction Design
- CHEMKIN made use of the GRImech version 3.0 reaction mechanism developed by the Gas Research Institute
- Assumptions
  - Chemical reactions occur within a closed volume or a combustion bomb and not in a cylinder
  - Initial composition of air, fuel, and NOx is homogenous
  - Pressure and temperature are chosen to mimic conditions near TDC

Fuel Burnout Rate

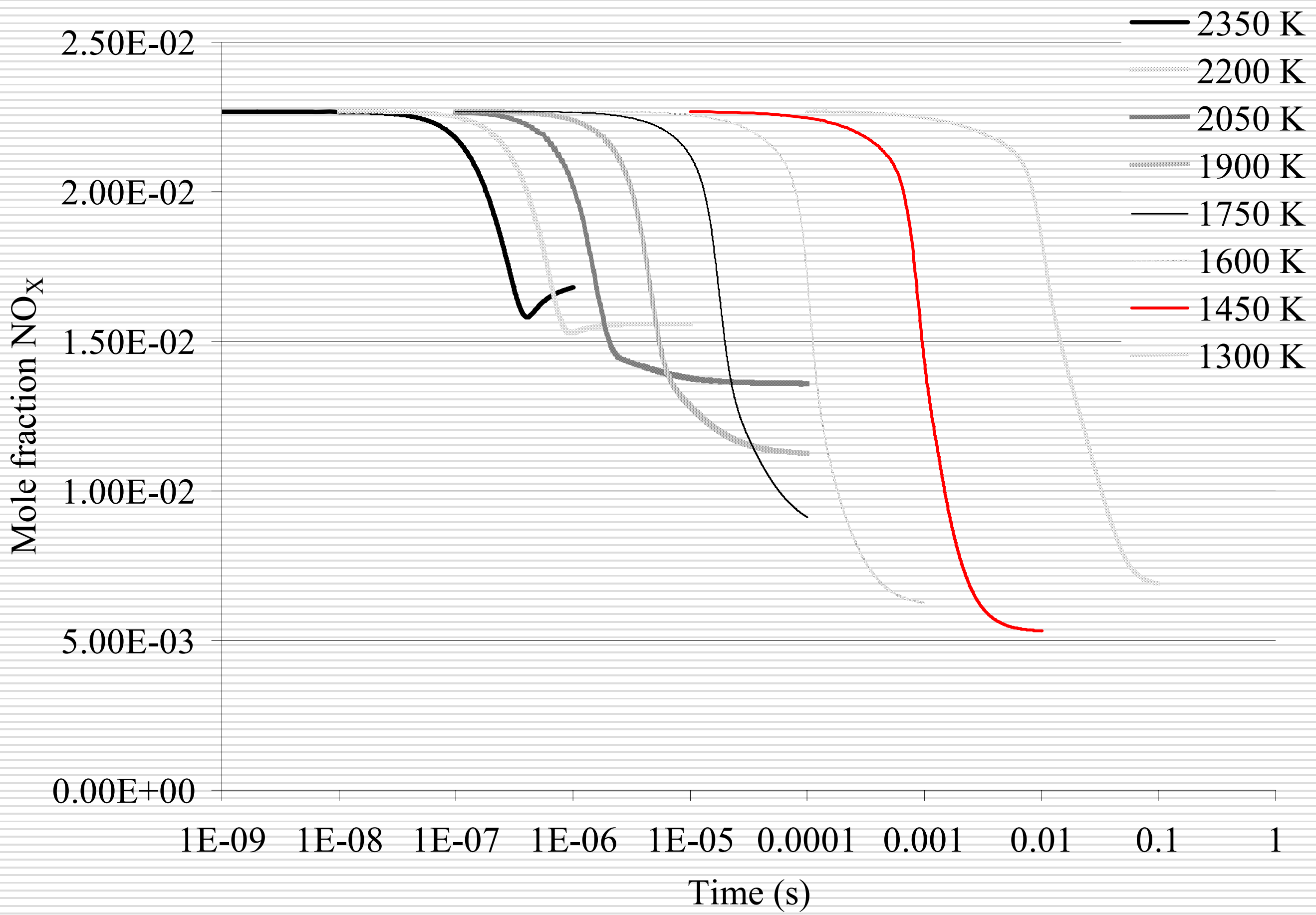


NOx Decomposition at λ=1.4

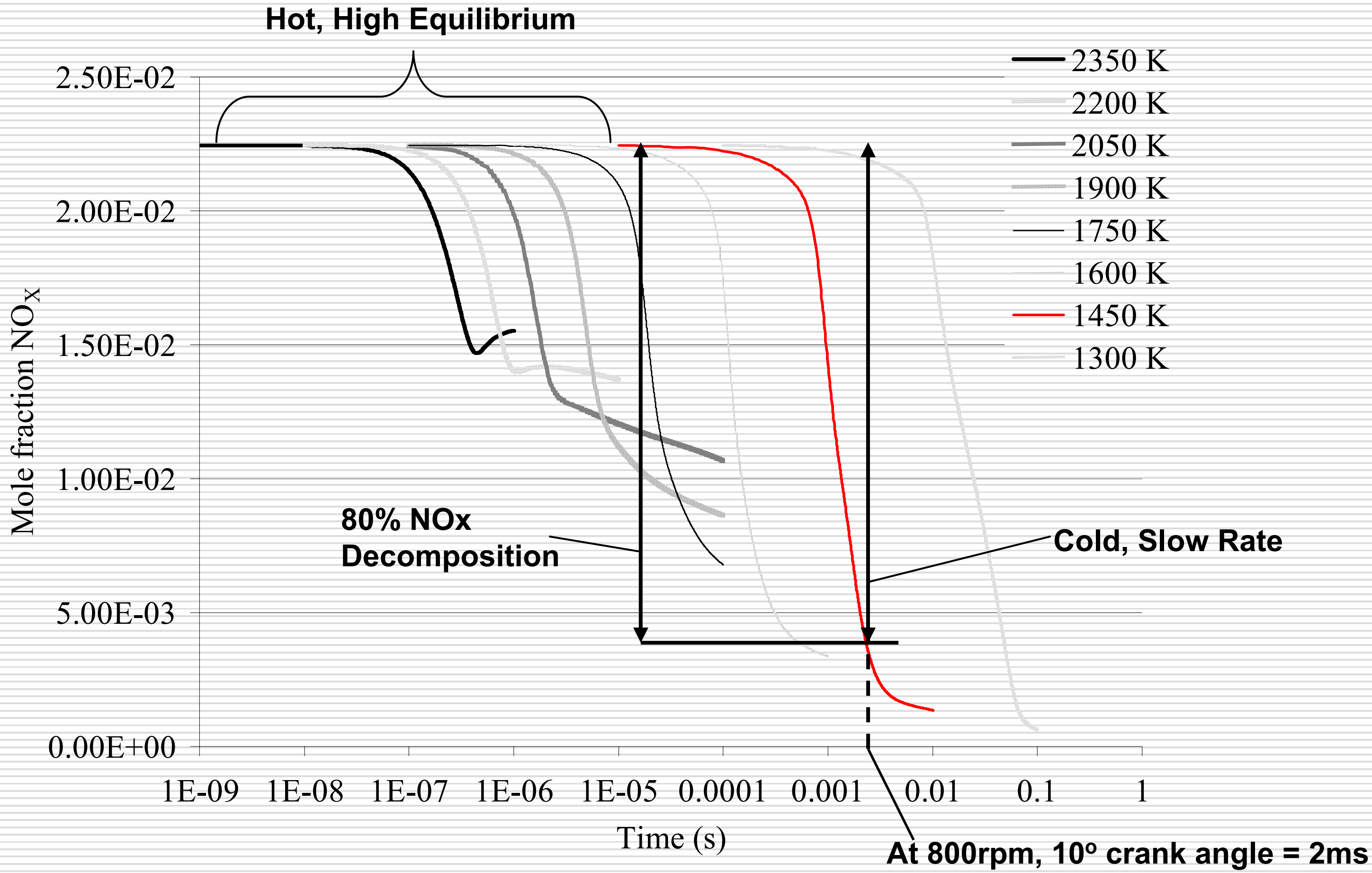


- Initial mole fractions of CH_4, O_2, N_2, NO in the mixture and volume were held constant

NOx Decomposition at λ=1 (Stoichiometric)



NOx Decomposition at λ=0.9



- Results of modeling were presented at Second Annual Advanced Stationary Reciprocating Engines Conference and at ORNL Workshop

Modeling Conclusions

- Software model predicted conversion rates between 20% and 25% for the lean operation, while experiments showed 14% and 25% for the natural gas engine

- Predicting NO_X levels on large time scales confirms that the NO_X conversion is rate limited rather than equilibrium limited

- The model showed that at rich conditions at an appropriate temperature, 80% decomposition levels can be expected

Ad Hoc Experiment (Test Engine -2)

- 1998 Honda GX390
- 13hp gasoline 4 stroke engine
- Single cylinder
- Stoichiometric / rich operation

Honda GX390 – NOx Injection Matrix

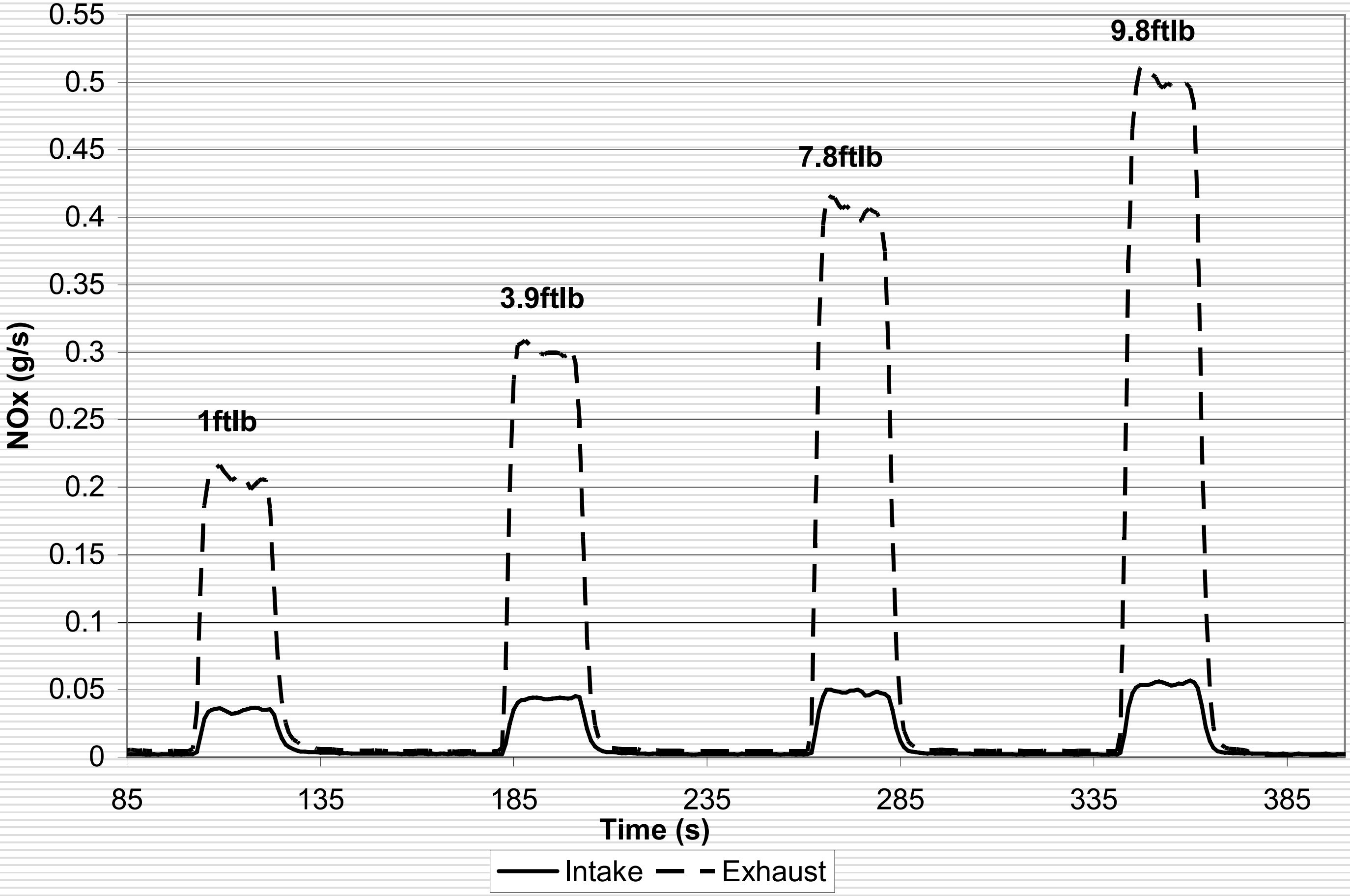
Test Engine	**Load (ft-lb)**	**Speed (rpm)**	**Injected NOx(%)**	**Air/Fuel Ratio**
Honda GX390	Varied 1.0 - 9.8	Constant 3600	Varied 1.0 – 75.0	Constant

Sample NOx Injection Matrix

Speed (rpm)	**Load (ft-lb)**	**NO% in Intake**	**Intake Flow Rate (lps)**
3600	1.0	5.0	4.4
3600	3.9	5.0	4.8
3600	7.8	5.0	5.8
3600	9.8	5.0	6.4

- Loads were calculated by accounting for the electrical loads and generator efficiency

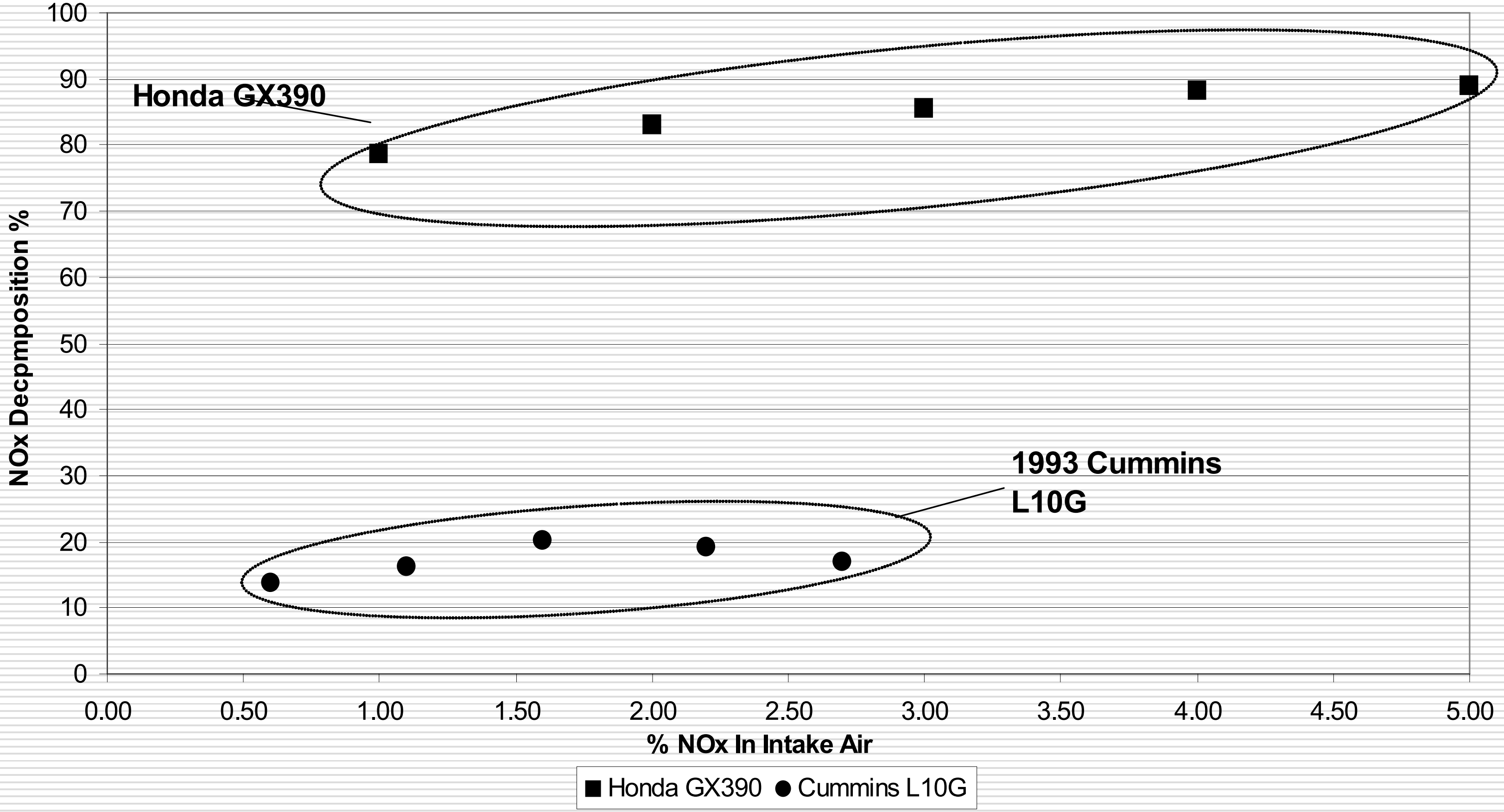
Honda GX390 - NOx Injections



Comparing NOx Injection Concentrations

- Contrasting rich gasoline with lean natural gas engine
  - 1993 Cummins L10
    - Injected NO concentration varied from 0.5% to 2.3% of the intake air at 800rpm and 400ft-lb
  - Honda GX390
    - Injected NO concentration varied from 1% to 5% of the intake air at 3600rpm and 9.8ft-lb

Effects of High NOx Injection Concentration on Honda GX390



Observations

- Exhaust gas temperature on the gasoline engine rose (80-110^{o}F) during NOx injections
- A significant exhaust gas temperature change was not observed on the 1993 Cummins L10G
- Hydrocarbon emissions varied on both engines during NOx injections
- There was no significant change in CO and CO_2 emissions during NOx injections

Experimental Conclusions with 1993 L10G and Ad Hoc Experiments

- It is possible to decompose NOx by passing it through an IC engine at sufficiently high concentrations
- Engine load and air/fuel ratio affected NOx decomposition on the 1993 Cummins L10G
- NOx injection concentration had a moderate affect on NOx decomposition on both engines
- In the gasoline engine, disassociation of NO made the combustion mixture leaner, thus raising the combustion temperature
- High NOx decomposition rates may be possible if a lean burn engine is operated at a stoichiometric air/fuel ratio with sufficient amount of EGR during the NOx decomposition phase (EGR can control temperature, knock and power density)

Use of Stoichiometric/Rich Operation

- Vision
  - EGR may be substituted for lean burn excess air
  - Engine can be operated on one or more cylinders in rich/stoichiometric mode only during NOx decomposition

- Concerns
  - Power/IMEP
  - Knock
  - Heat release and misfire
  - Engine deterioration

Stoichiometric/Rich Operation of Natural Gas (Test Engine – 3)

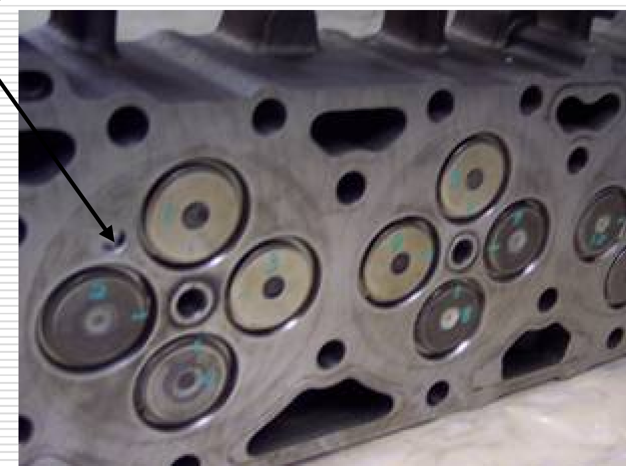
- 1998 Cummins L10 280G
- Inline 6 cylinder
- Spark ignited
- Turbocharged
- Electronically managed
- Closed-loop fuel injected

Engine Modifications for In-Cylinder Pressure Measurement

Cylinder head was rebuilt and modified by Cummins Inc.

- Kistler type 6067C cylinder pressure sensor installed on cylinder #1

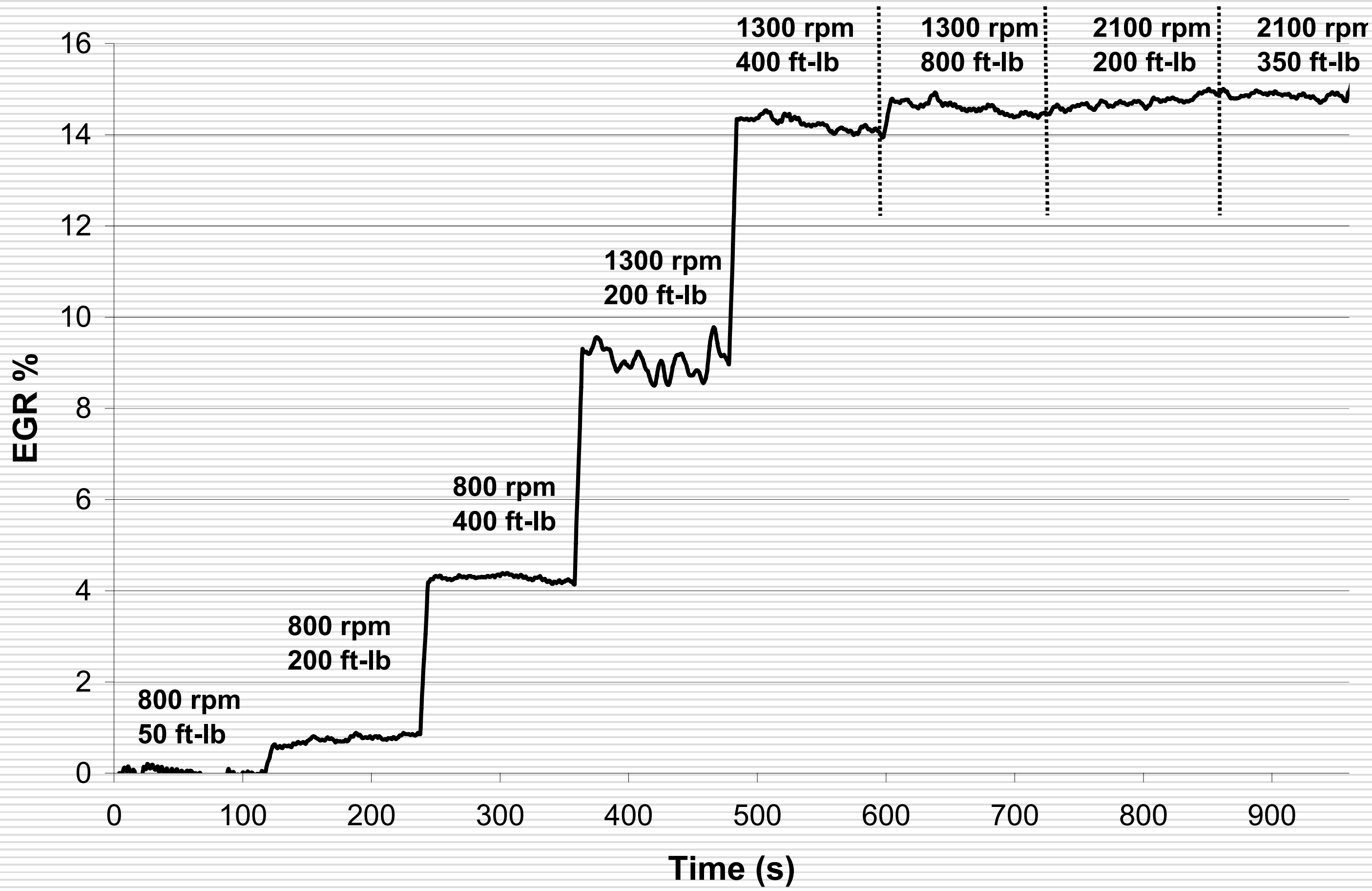
Pressure sensor port on cylinder head



Other Engine Modifications

- EGR
  - Low pressure to low pressure EGR was utilized
  - EGR percentage was calculated by taking the ratio of CO_2 concentration measured in the raw exhaust and at the engine intake
  - EGR percentage was up to 14%
- Air/fuel ratio
  - A circuit was constructed to emulate the signal from the OEM wide range O_2 sensor to control the fueling of the engine at adjustable values
- In-cylinder NOx measurement
  - In-cylinder NOx was measured continuously using a Cambustion "fast NOx analyzer" fed through a modified spark plug installed in cylinder #6

EGR Percentage for Each Engine Operating Point

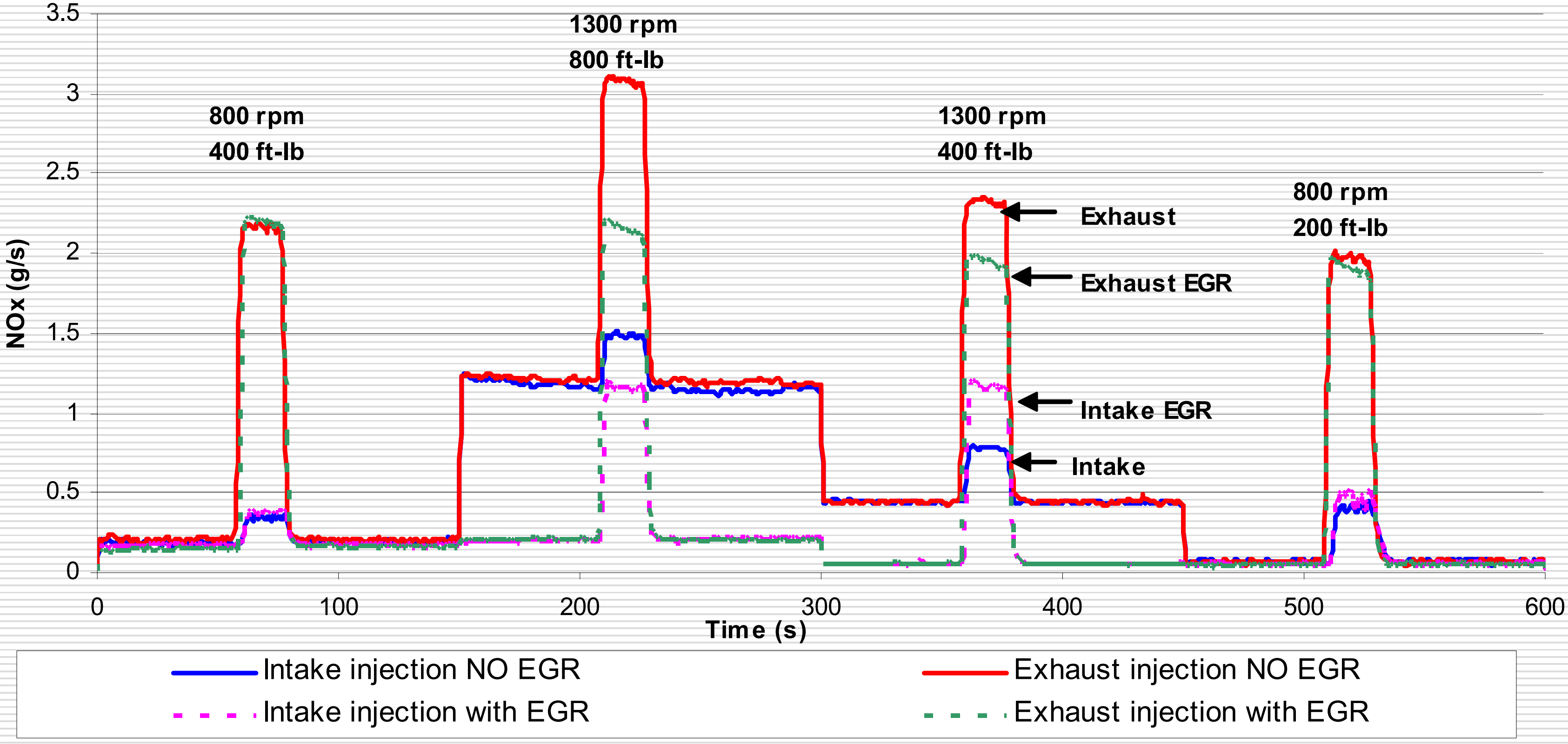


Test Matrix for 1998 Cummins L10G

	Engine Horse Power (hp)	Speed (rpm)	Load (ft-lb)	Baseline Runs		NOx Decomposition Using Bottled NO	
				Rich	Rich EGR	Rich	Rich EGR
Low Speeds	8	800	50	X	X	X	X
	30	800	200	X	X	X	X
	60	800	400	X	X	X	X
Intermediate Speeds	50	1300	200	X	X	X	X
	100	1300	400	X	X	X	X
	200	1300	800	X	X	X	X
Rated Speeds	60	2100	150	X	X	X	X
	140	2100	350	X	X	X	X

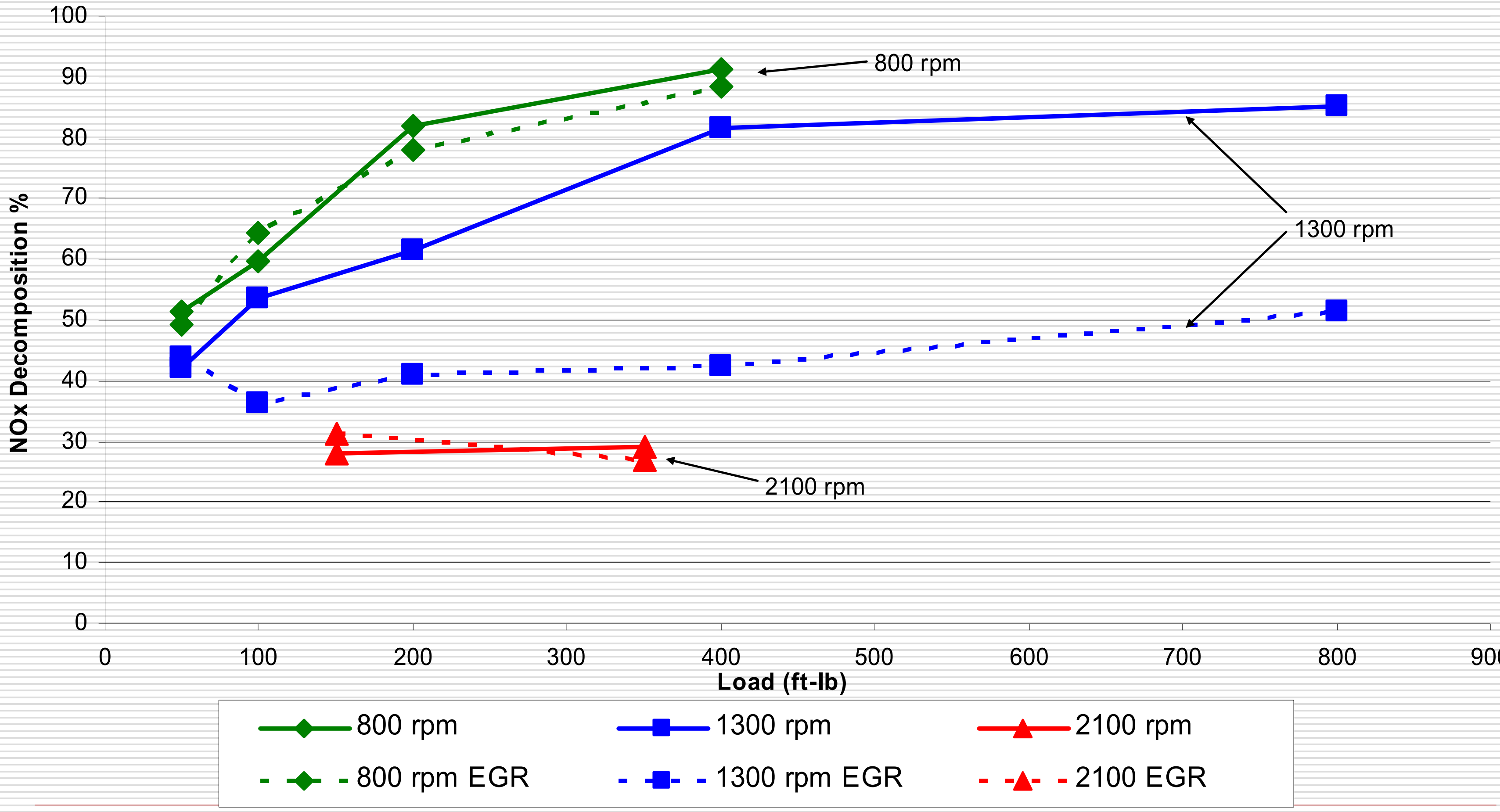
- Emphasis was placed on running the engine close to stoichiometric and with EGR at an air/fuel ratio of 0.97 (slightly rich)

NOx Injections at Low, Intermediate, and Rated Speeds with High Loads

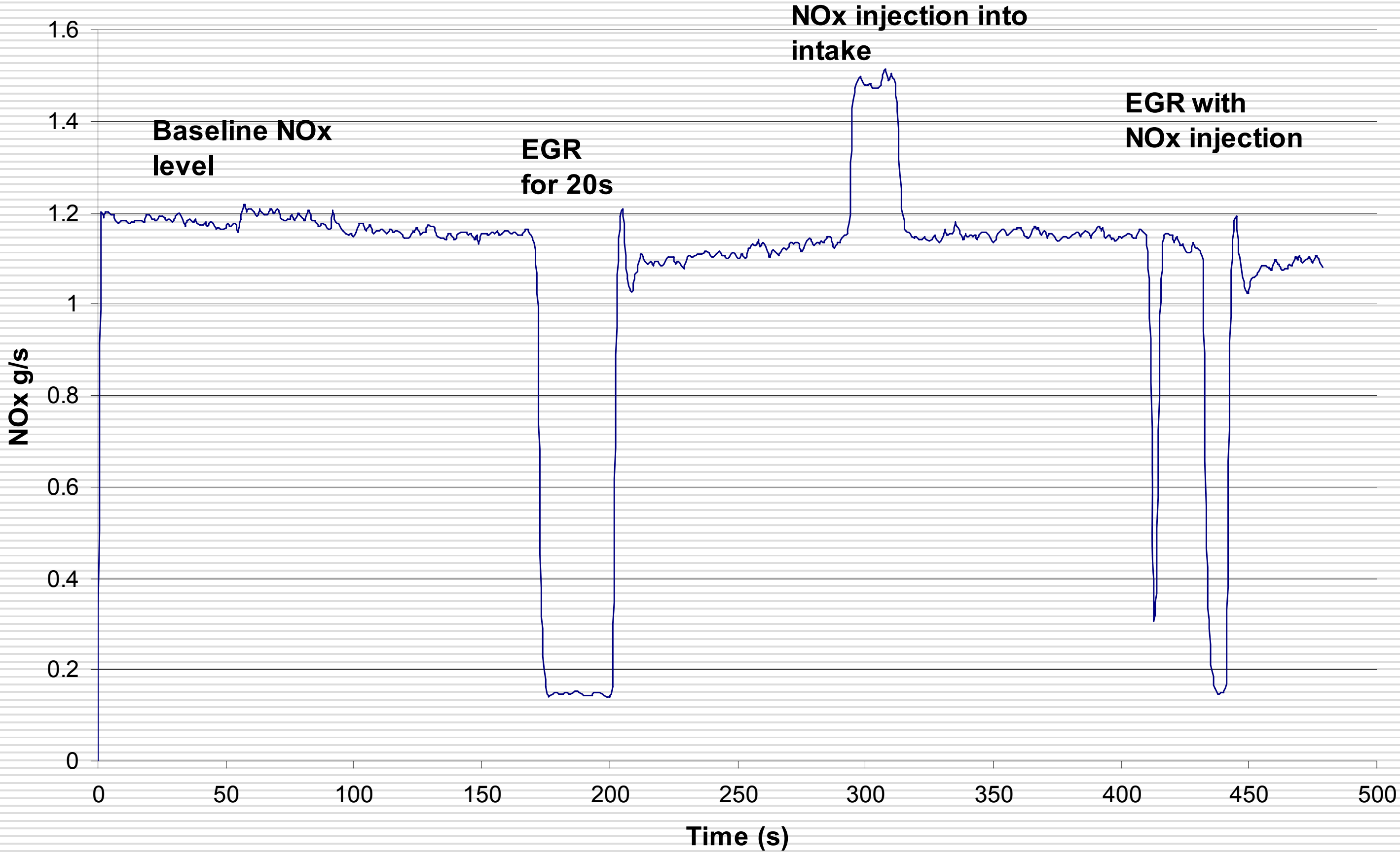


- Similar tests were conducted with lower loads

Summary of NOx Decomposition Rates at λ = 0.97



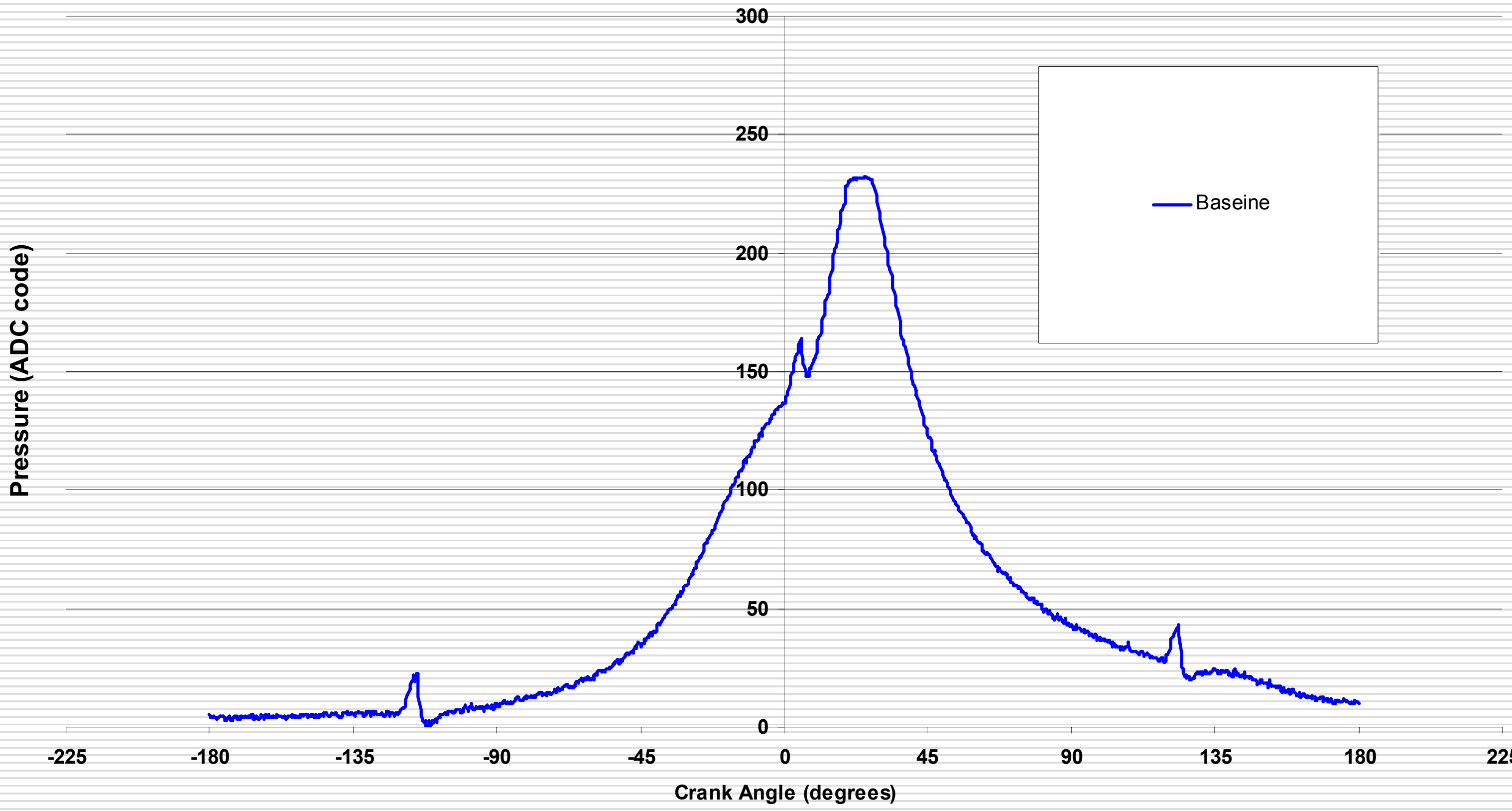
Influence of EGR on NOx Decomposition at 1300rpm, 800ft-lb



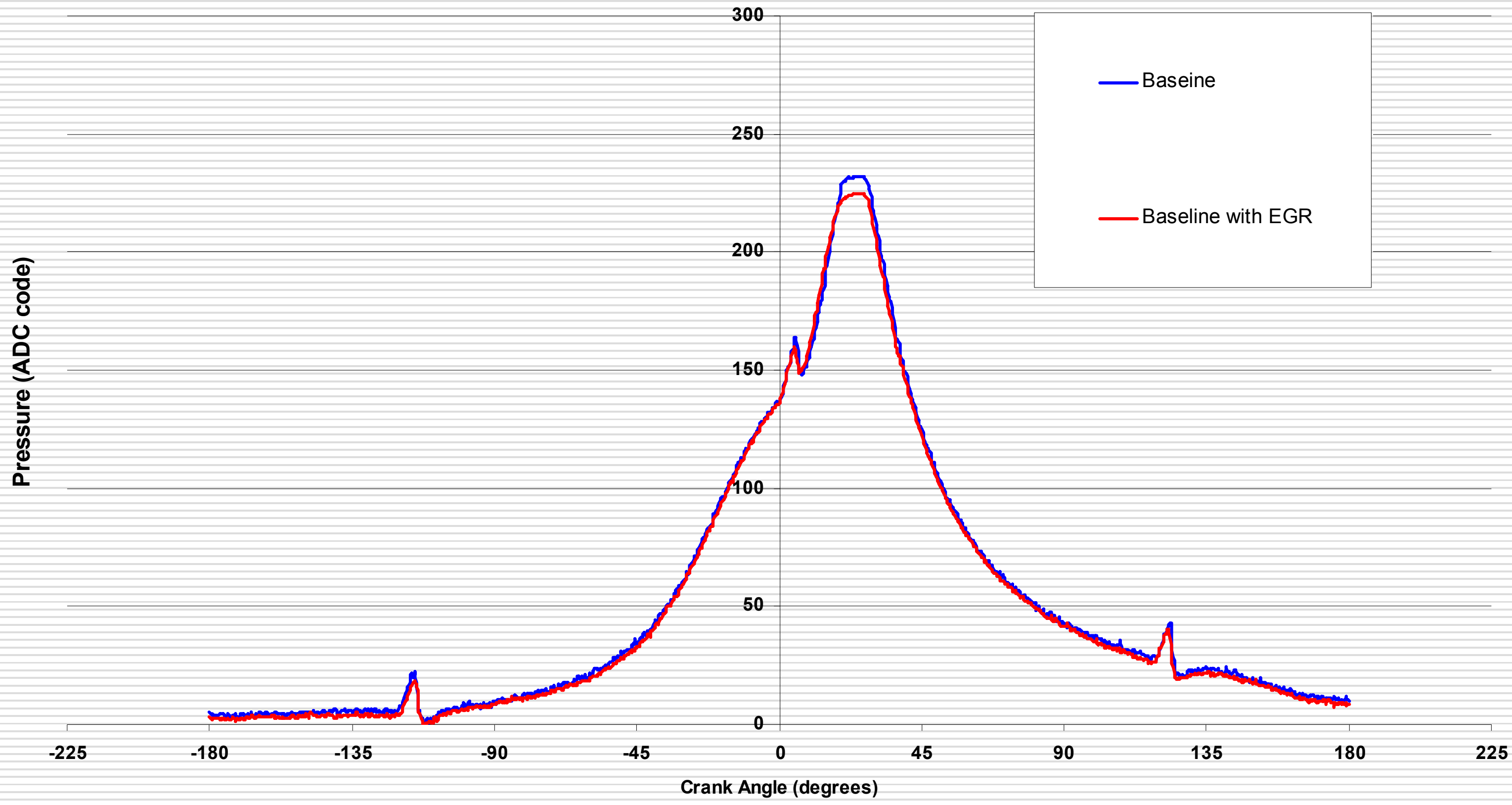
Summary of NOx Decomposition Rates at $\lambda = 0.97$

- Overall NOx decomposition percentages were between 28% and 91%
- Highest NOx decomposition was at low speed and high load (800 rpm and 400 ft-lb)
- Lowest NOx decomposition was at rated speeds (2100 rpm)
- These decomposition rates were corroborated with CHEMKIN modeling data, for stoichiometric or slightly rich operation

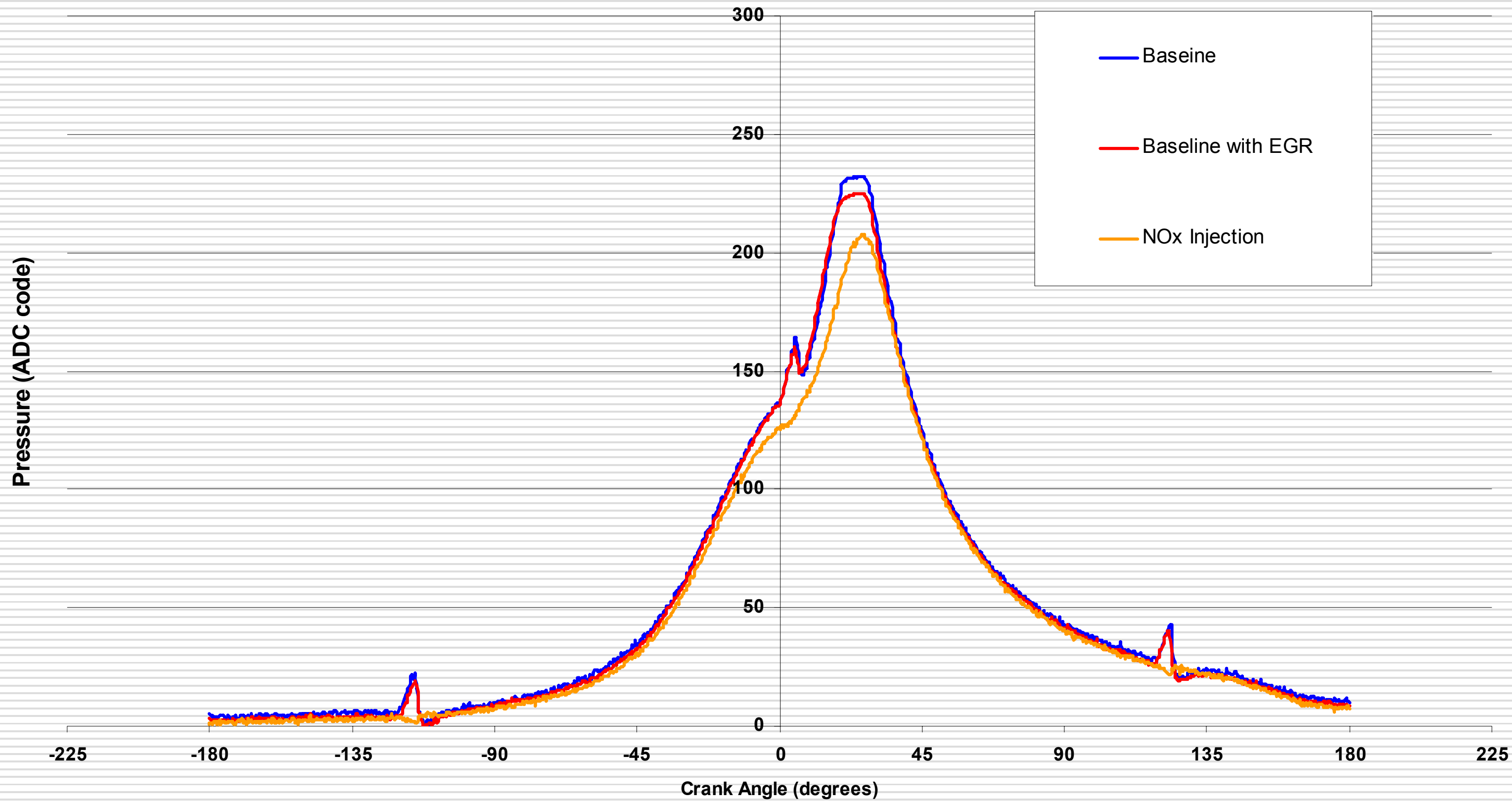
In-cylinder Pressure Plots at 800rpm, 200ft-lb



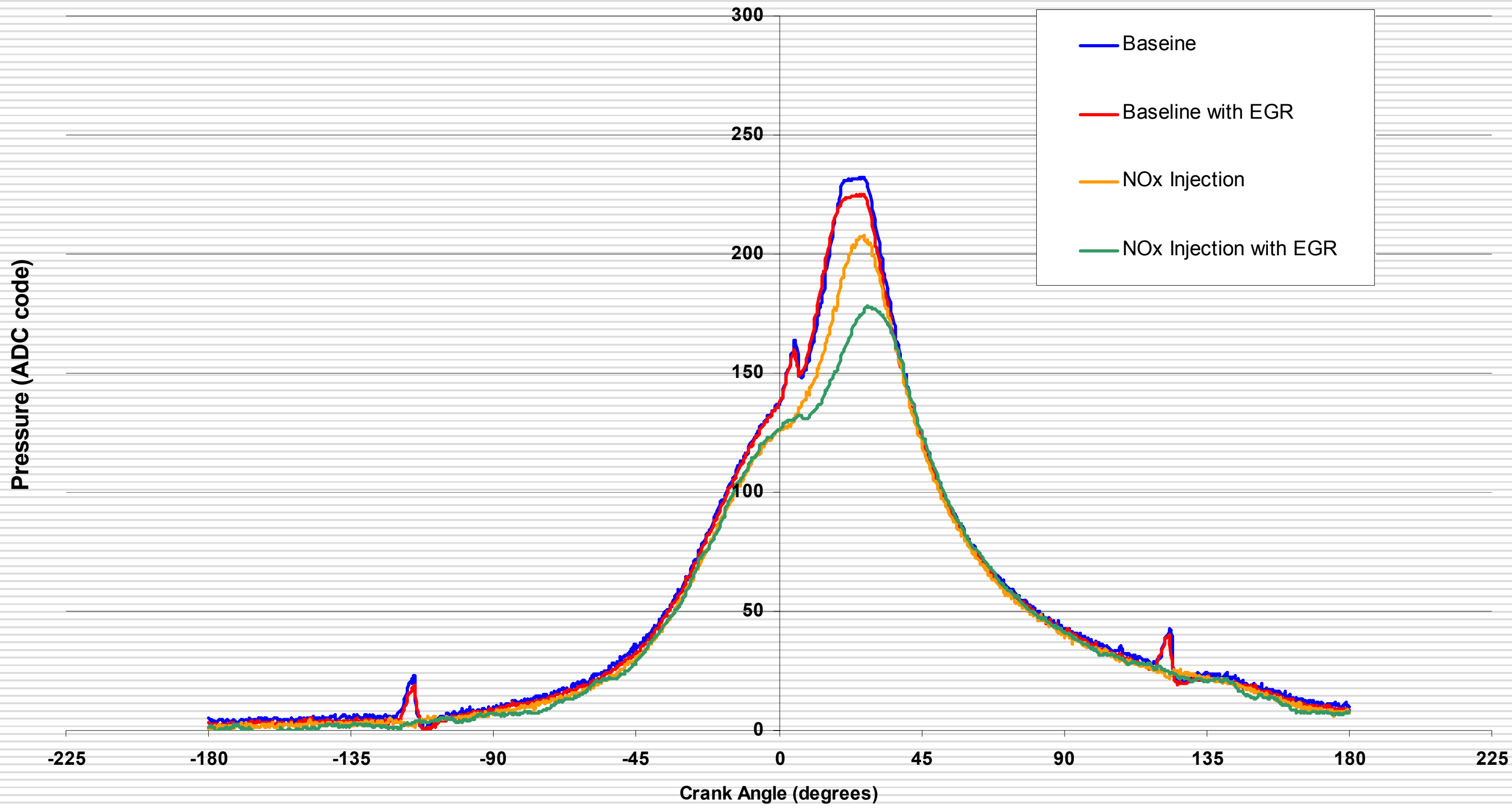
In-cylinder Pressure Plots at 800rpm, 200ft-lb



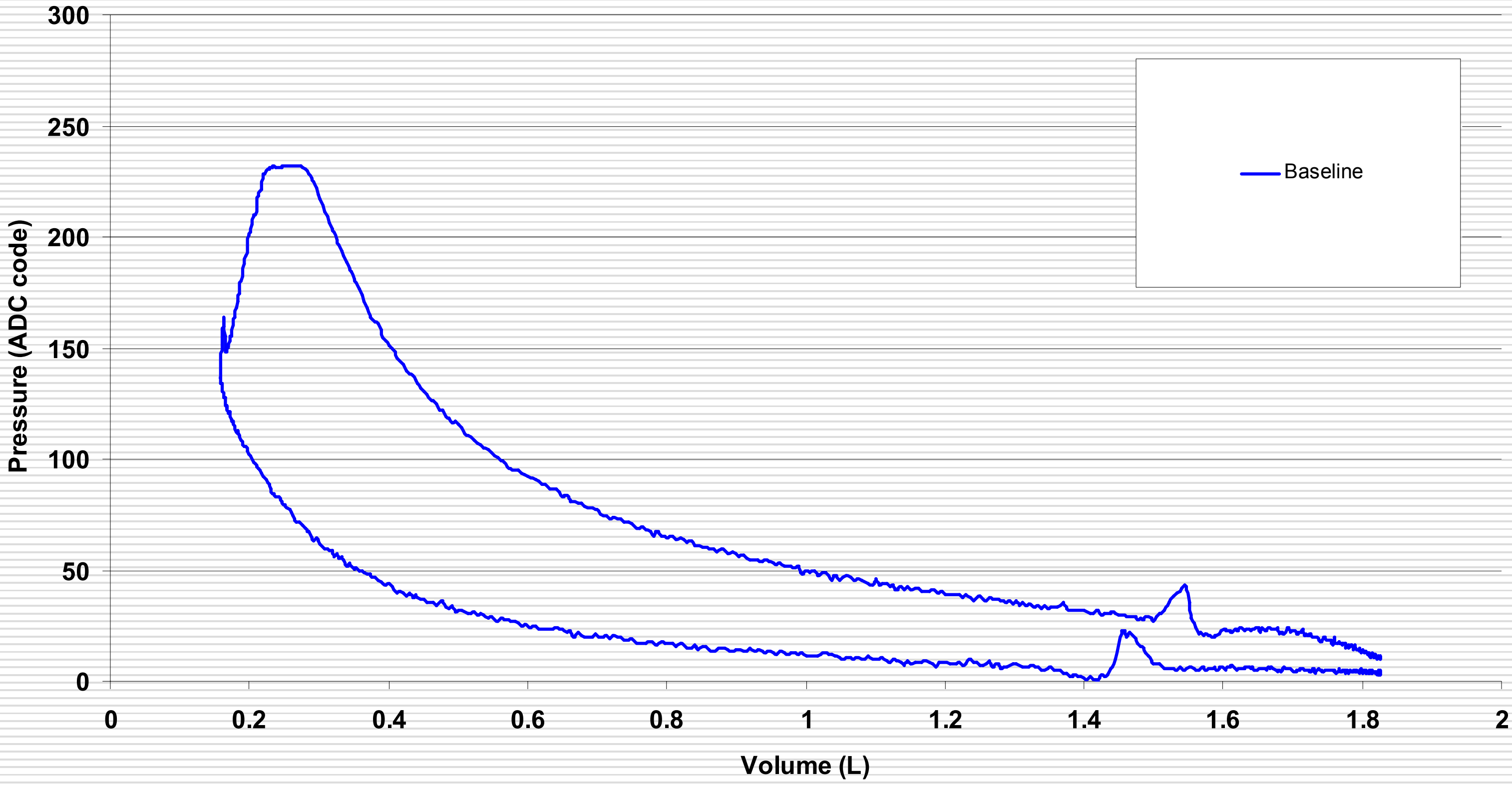
In-cylinder Pressure Plots at 800rpm, 200ft-lb



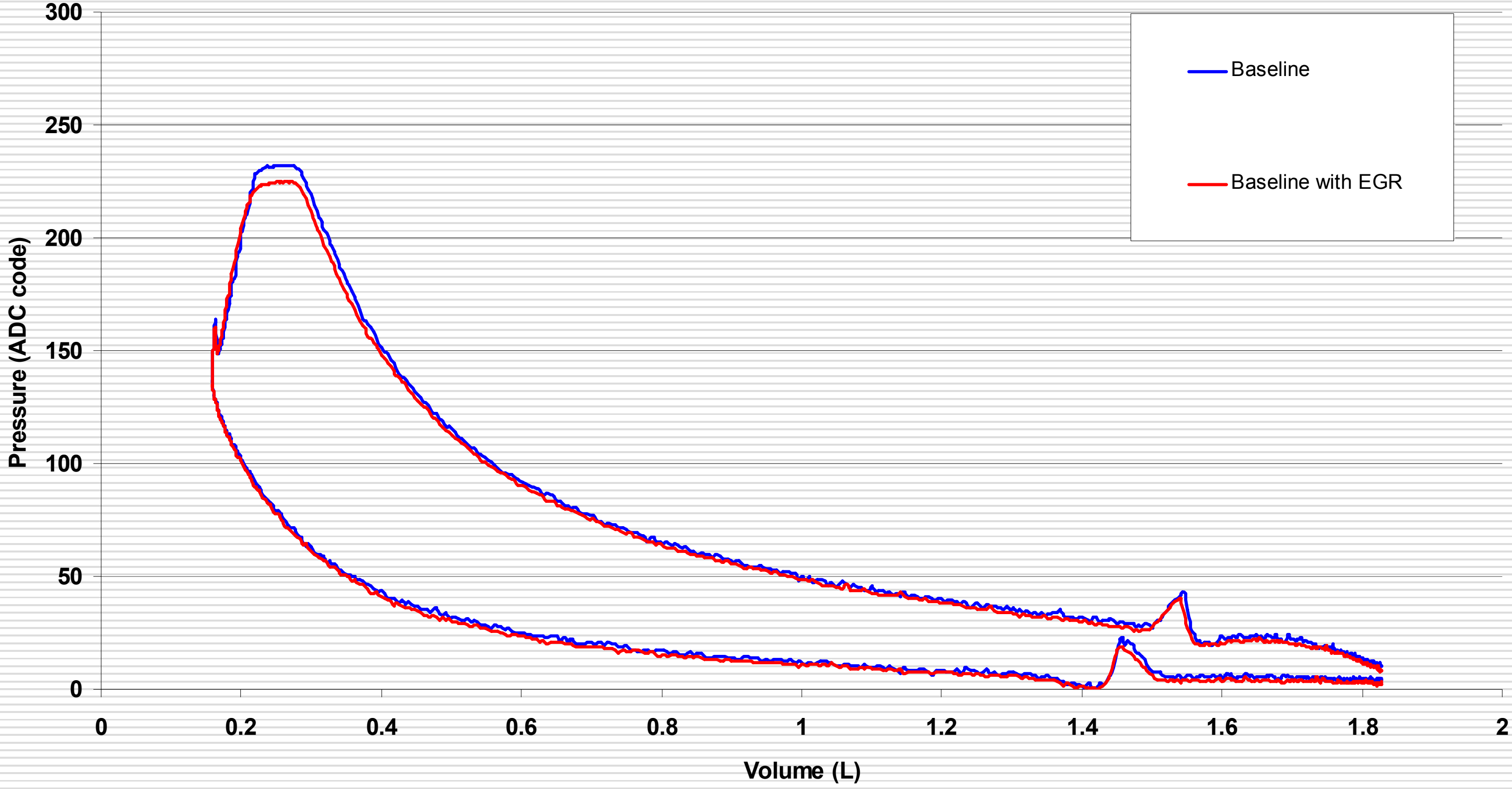
In-cylinder Pressure Plots at 800rpm, 200ft-lb



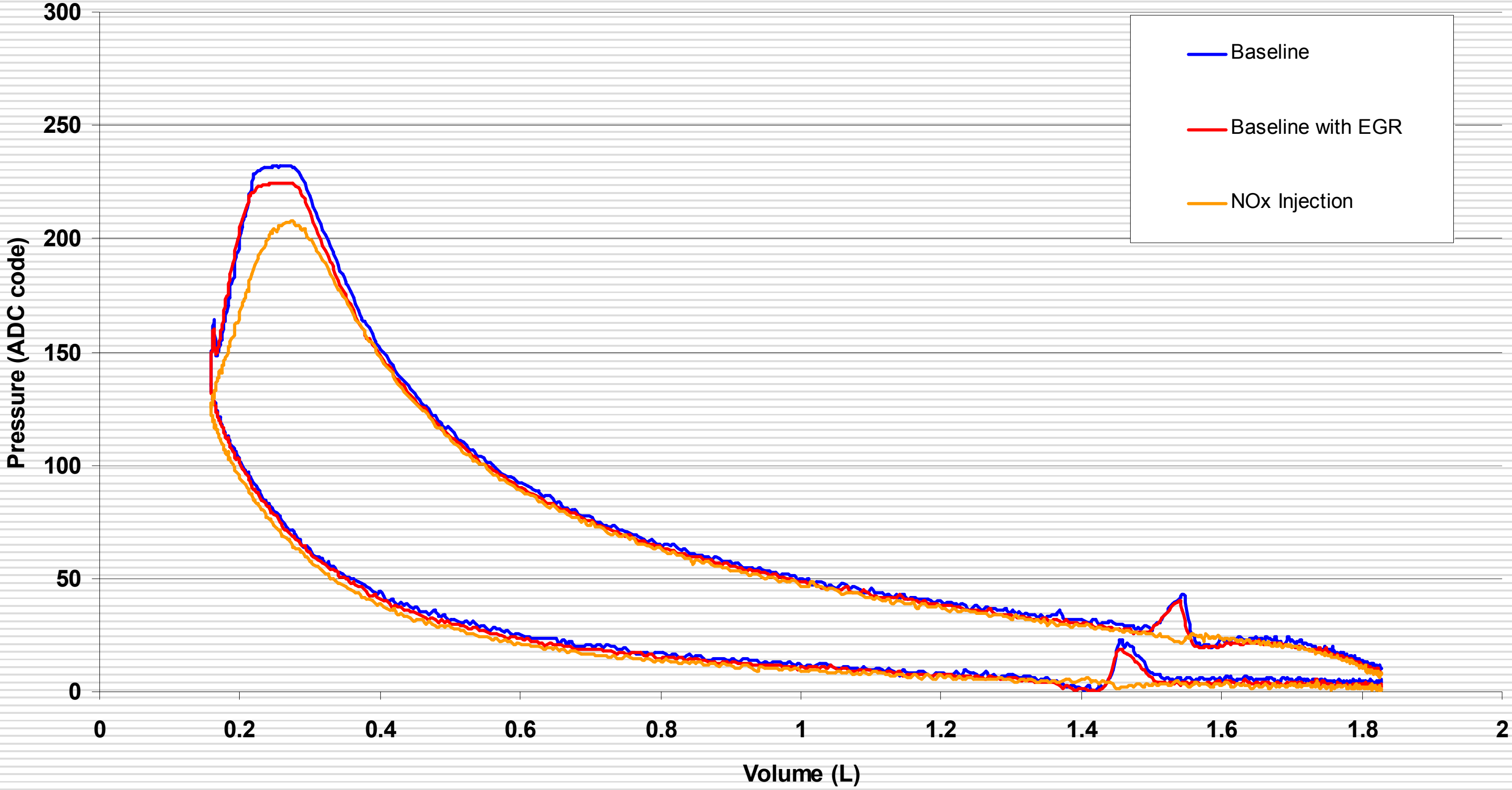
PV Diagrams at 800rpm, 200ft-lb



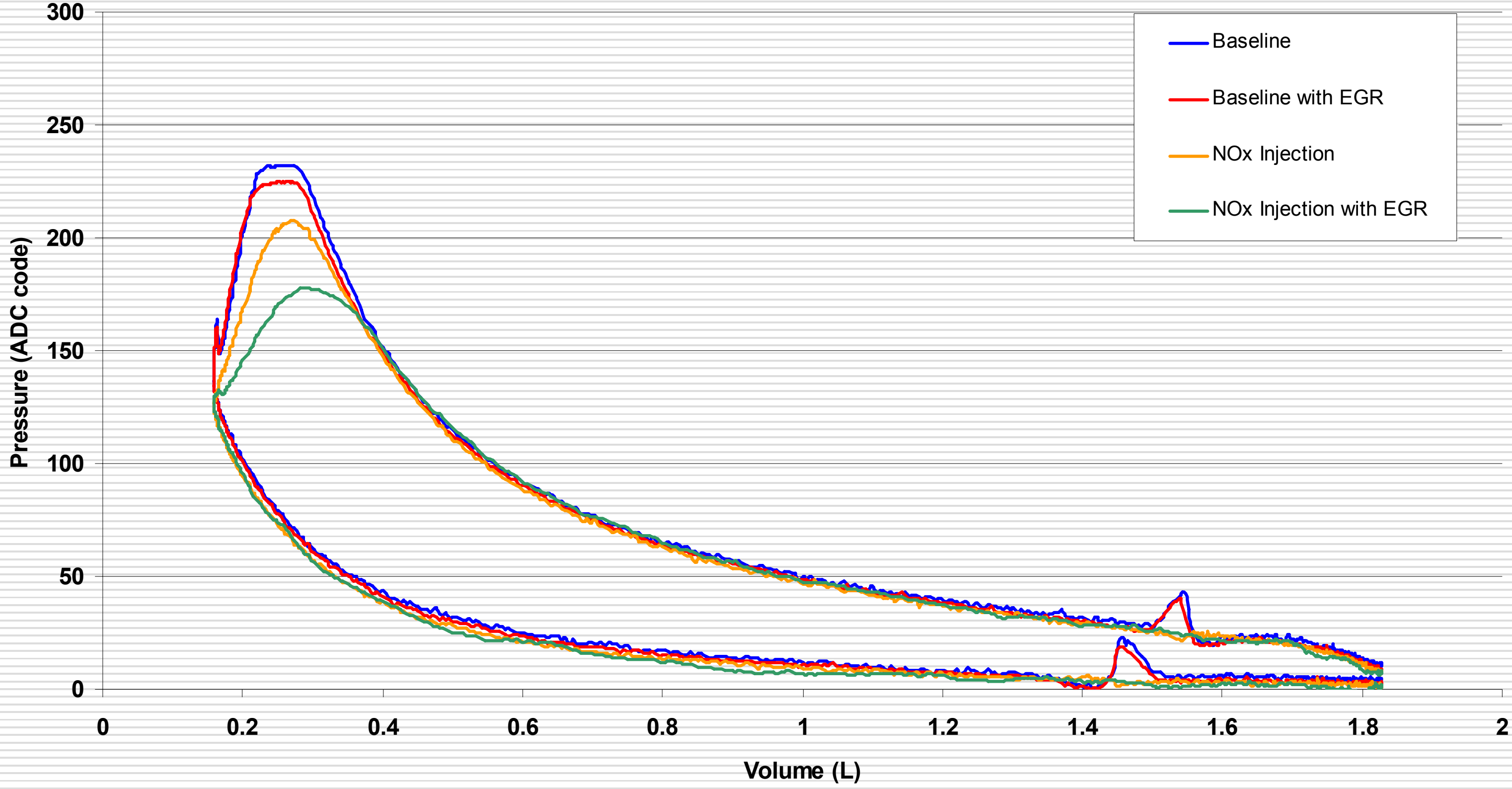
PV Diagrams at 800rpm, 200ft-lb



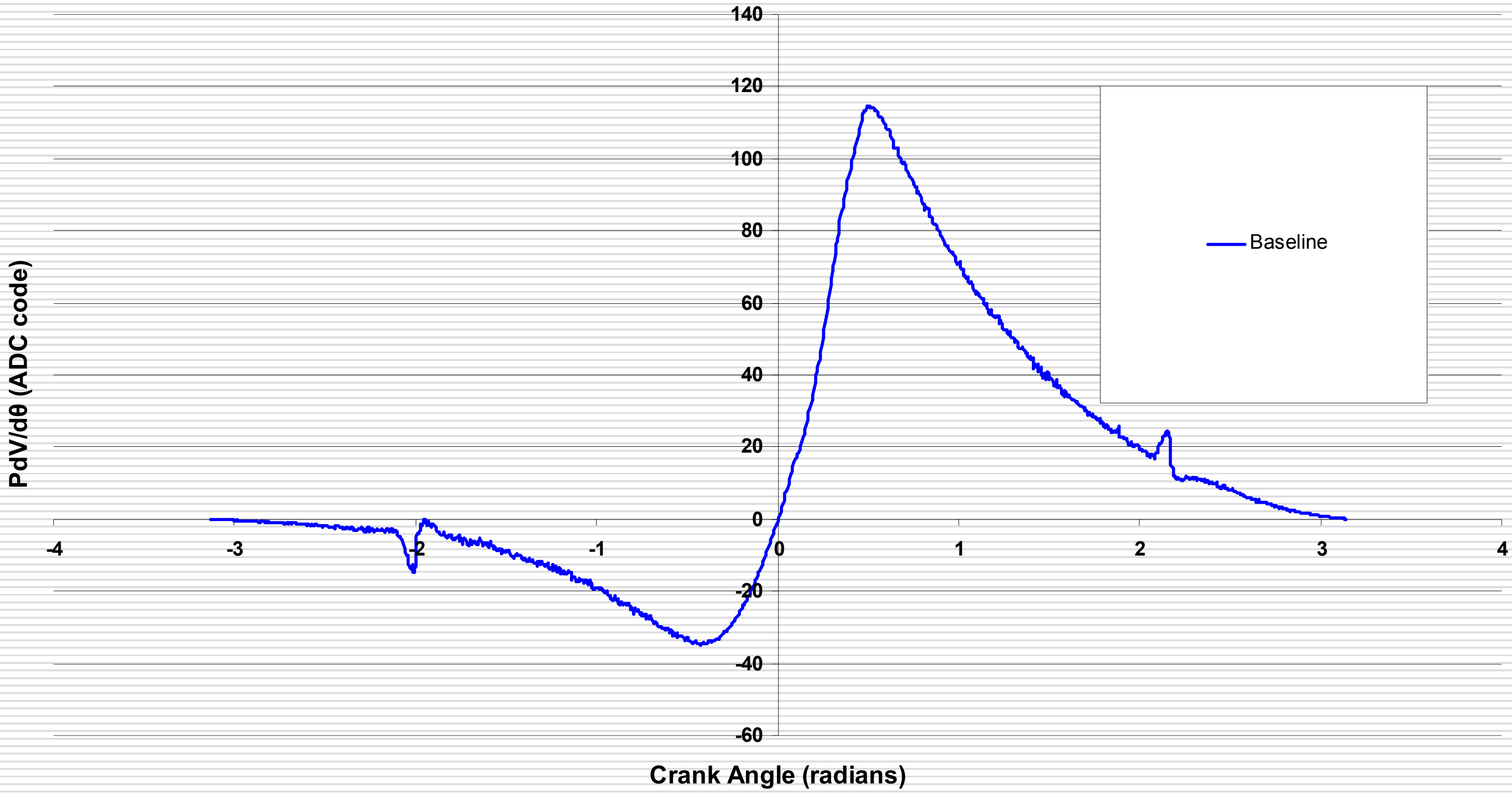
PV Diagrams at 800rpm, 200ft-lb



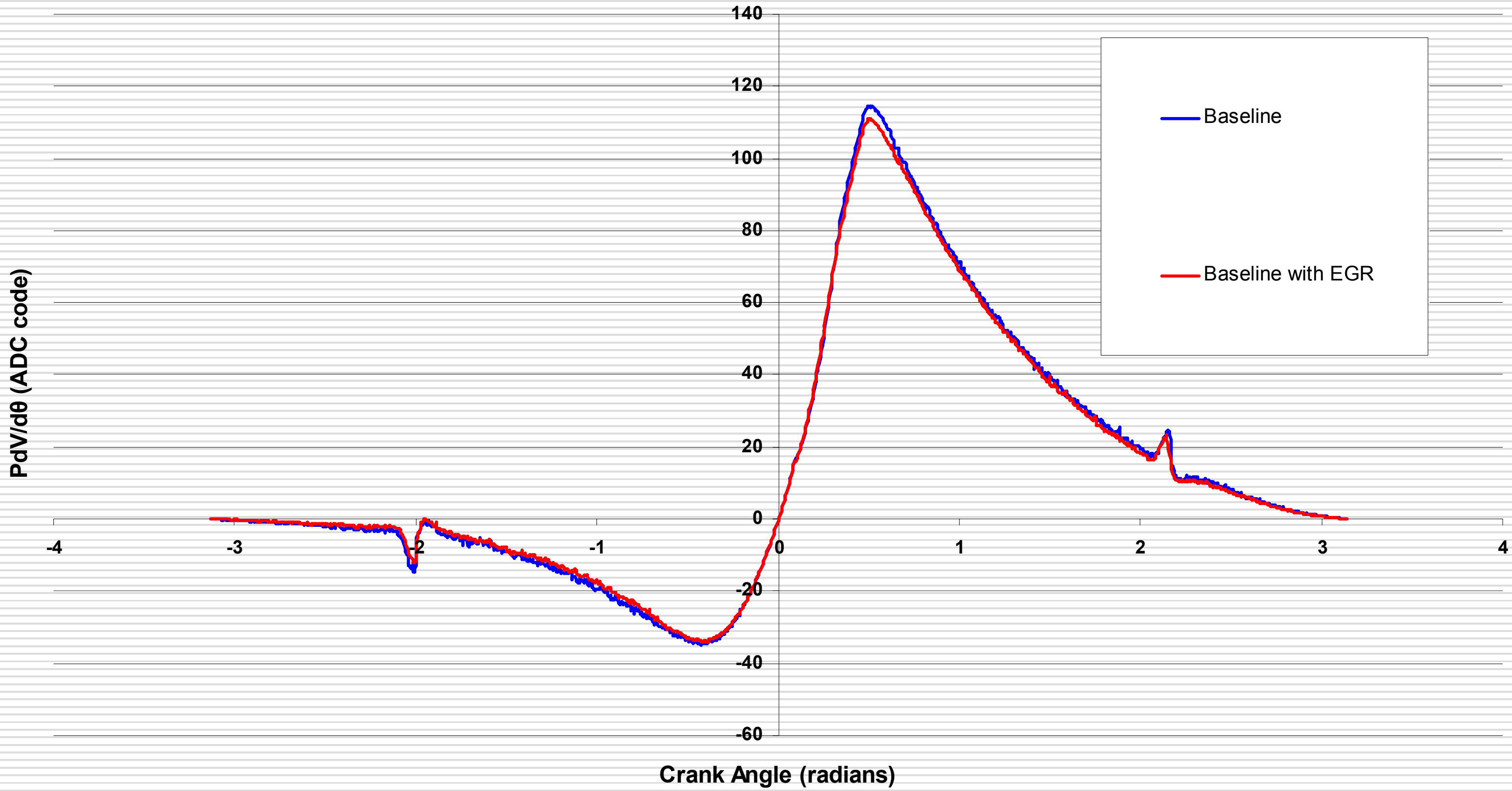
PV Diagrams at 800rpm, 200ft-lb



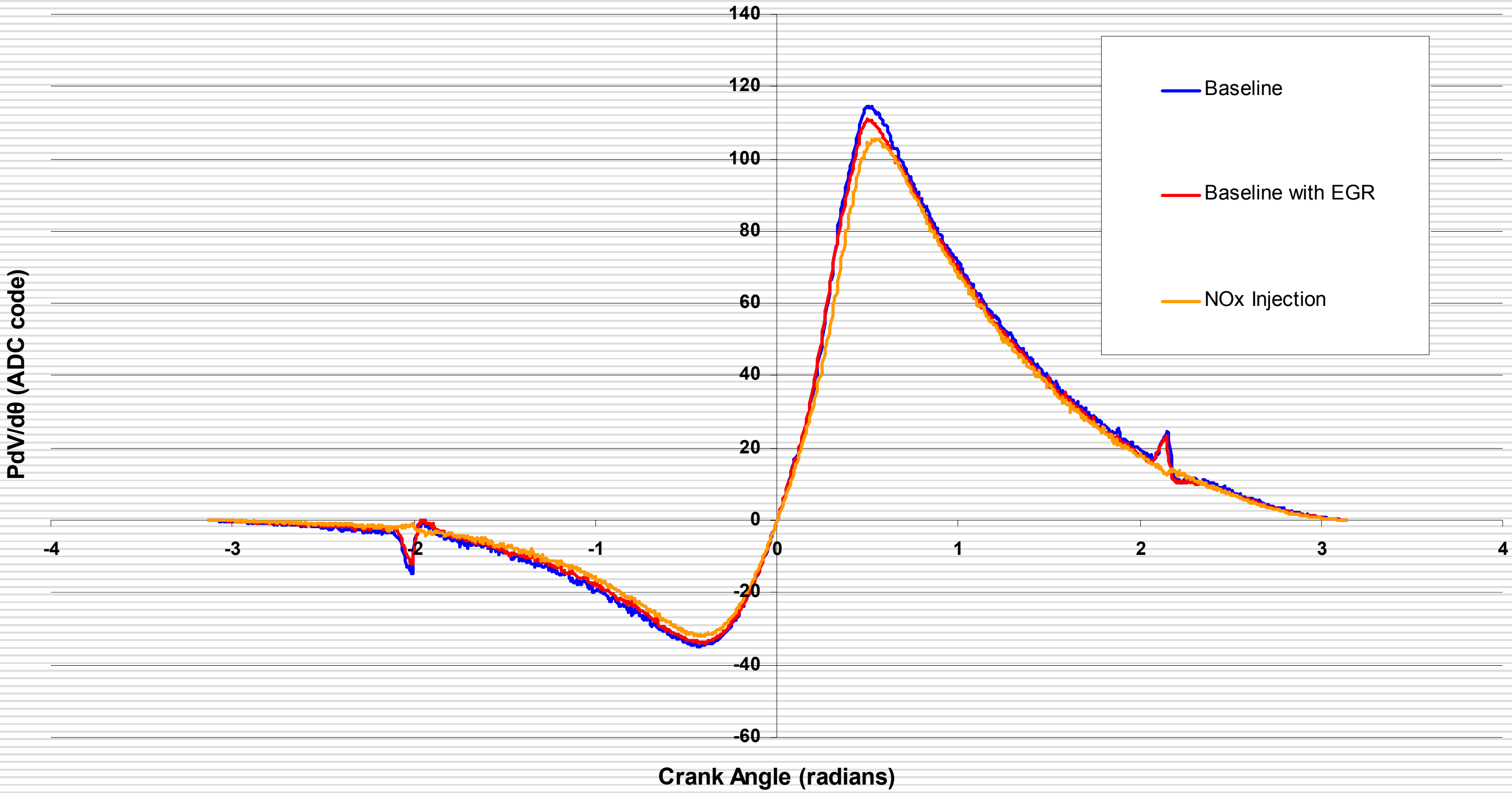
Work Done (Pdv/dθ) at 800rpm, 200ft-lb



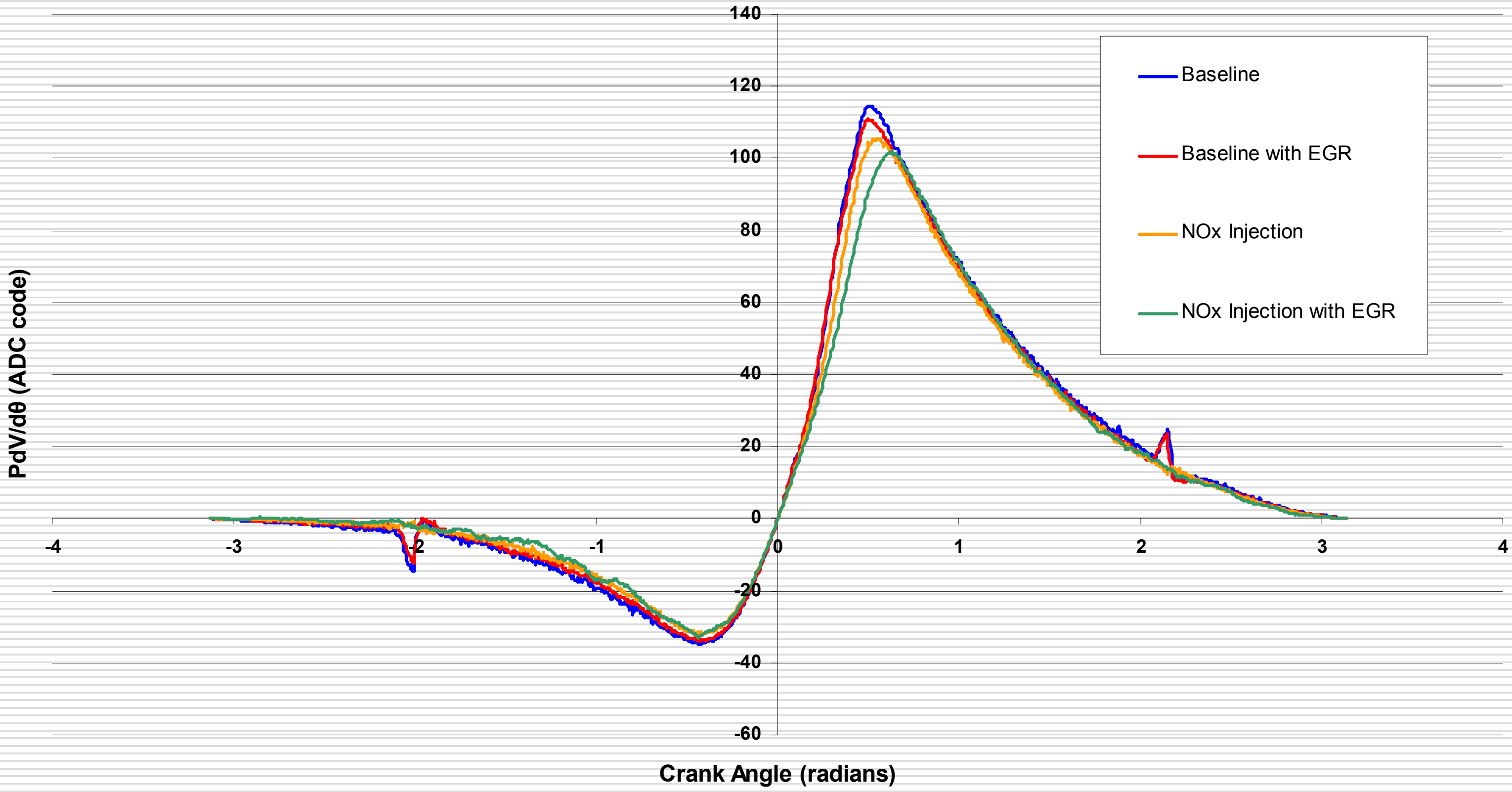
Work Done (Pdv/dθ) at 800rpm, 200ft-lb



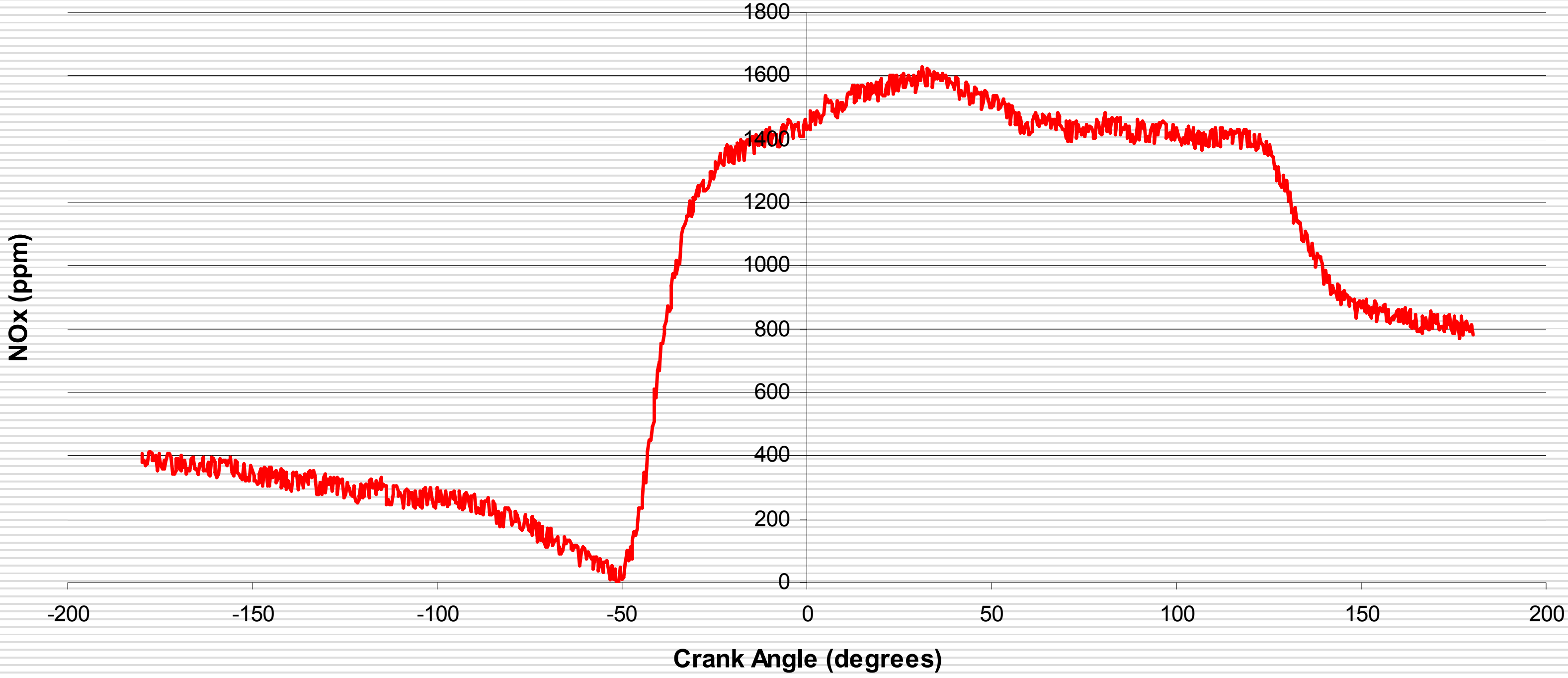
Work Done (Pdv/dθ) at 800rpm, 200ft-lb



Work Done (Pdv/dθ) at 800rpm, 200ft-lb



In-cylinder NOx Measurement

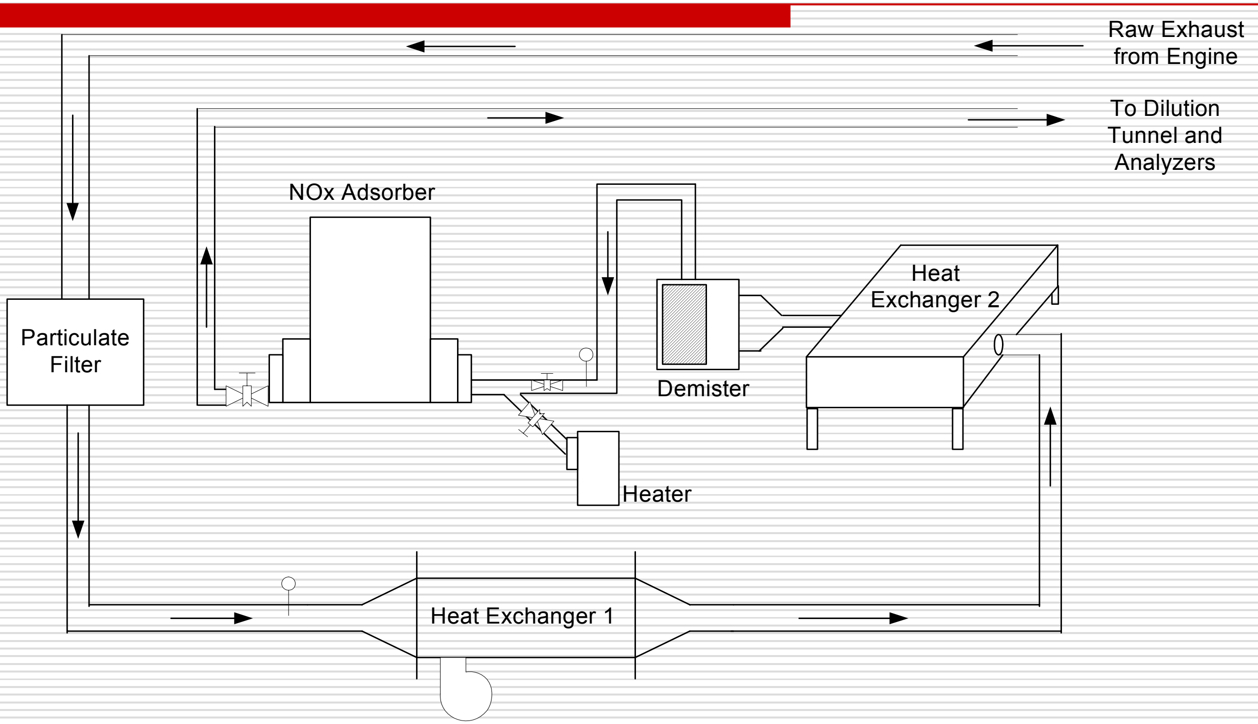


- In-cylinder NOx was measured using a Cambustion "fast NOx analyzer" fed through a modified spark plug installed in cylinder #6

NOx Decomposition Research

- Data processing and data quality control are not yet complete
- Additional runs are planned to clarify the role of EGR

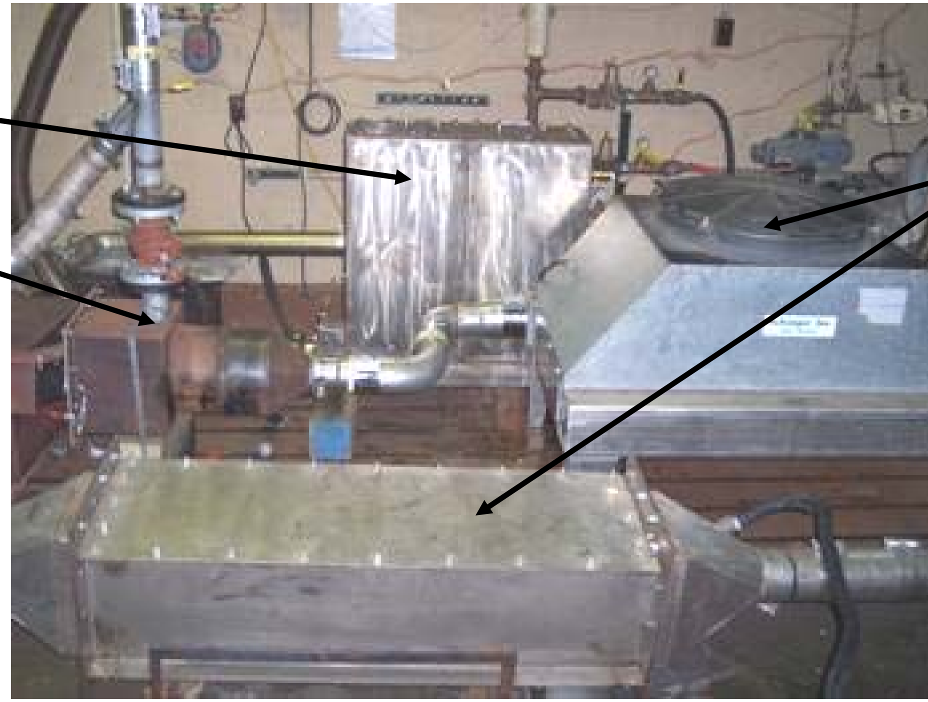
NOx Adsorbtion System



- Raw exhaust from the engine directed to the NOx adsorber through a particulate filter, two heat exchangers and a demister
- Exhaust from the adsorber sampled in the dilution tunnel, and compared with baseline NOx level for the same operating condition
- Adsorption equipment supplied by Sorbent Technologies

NOx Adsorber

Demister



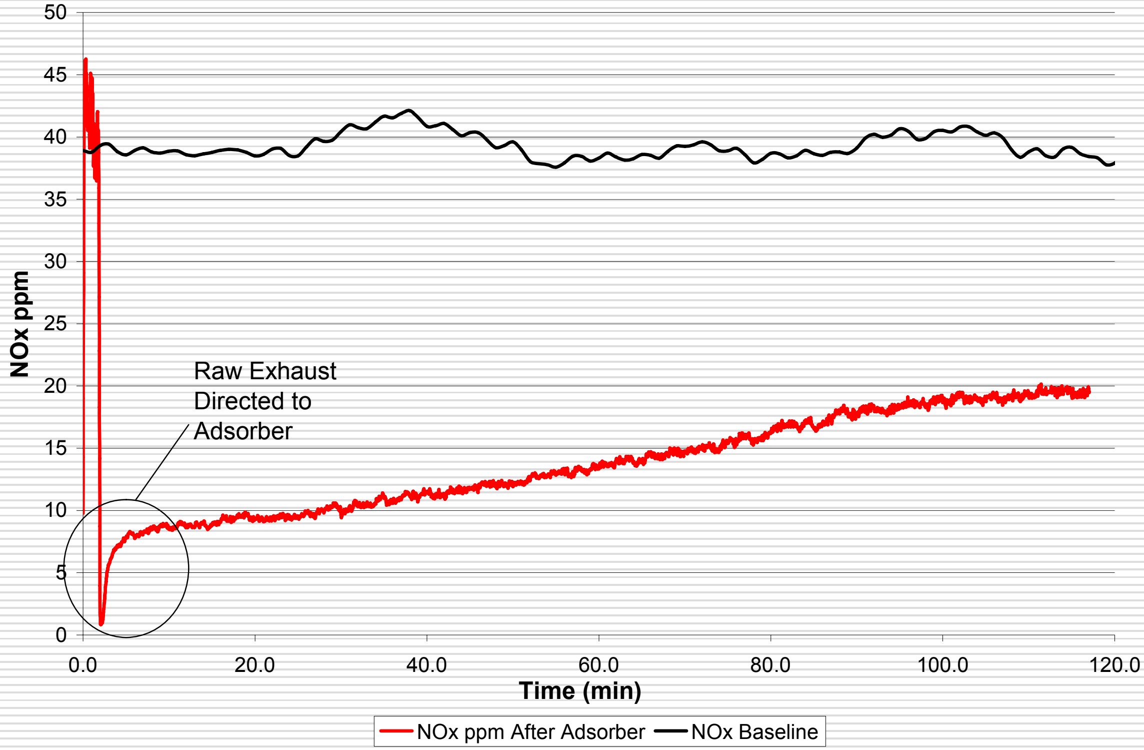
Heat

Exchangers

NOx
Adsorber

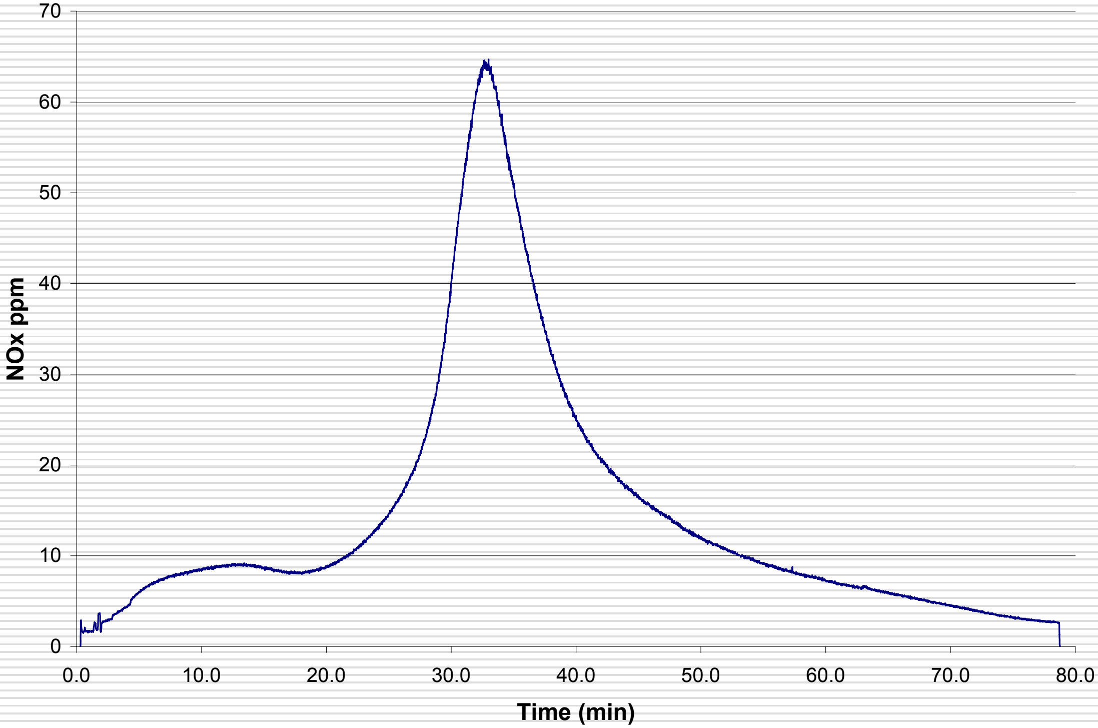
Hot Air
Blower

NOx Adsorber Loading at 800 rpm and 200 ft-lb



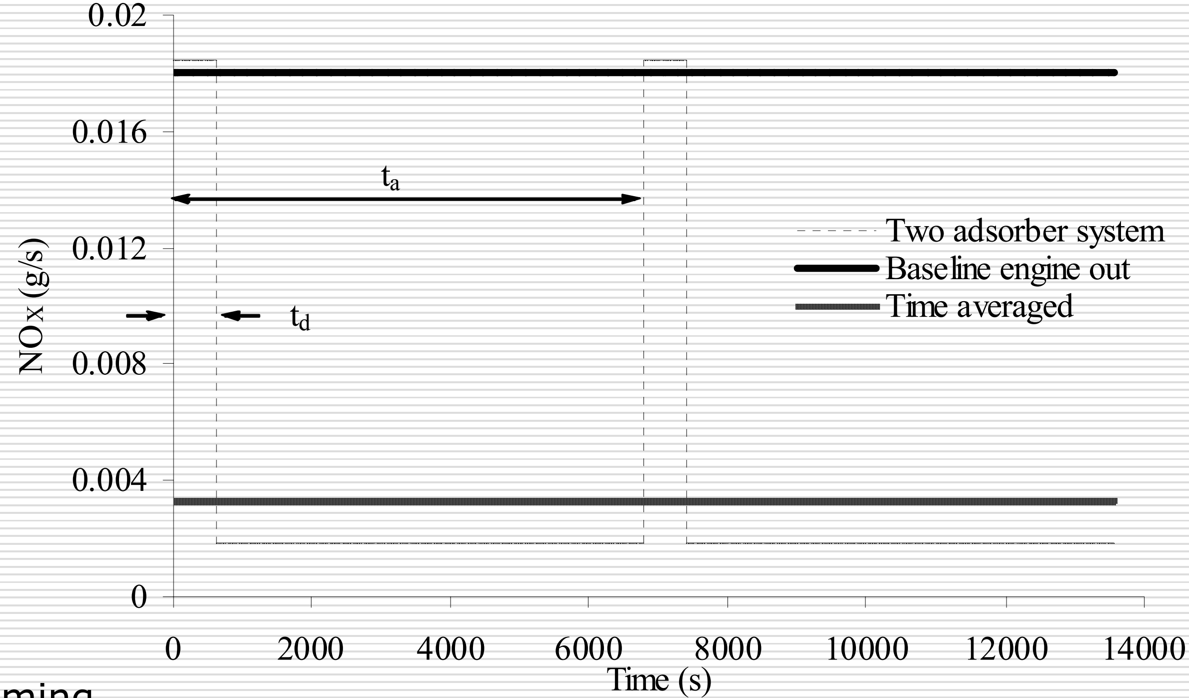
- Adsorber was loaded for 120 minutes
- Adsorbtion temperature under 100 ^{o}F
- 60 lbs of sorbent material

NOx Adsorber Desorption Phase



- NOx Adsorber was desorbed using the hot air blower and sampled at the dilution tunnel
- Flow rate 170 CFM at 660 ^{o}F
- More rapid, higher concentration NOx desorption is desirable

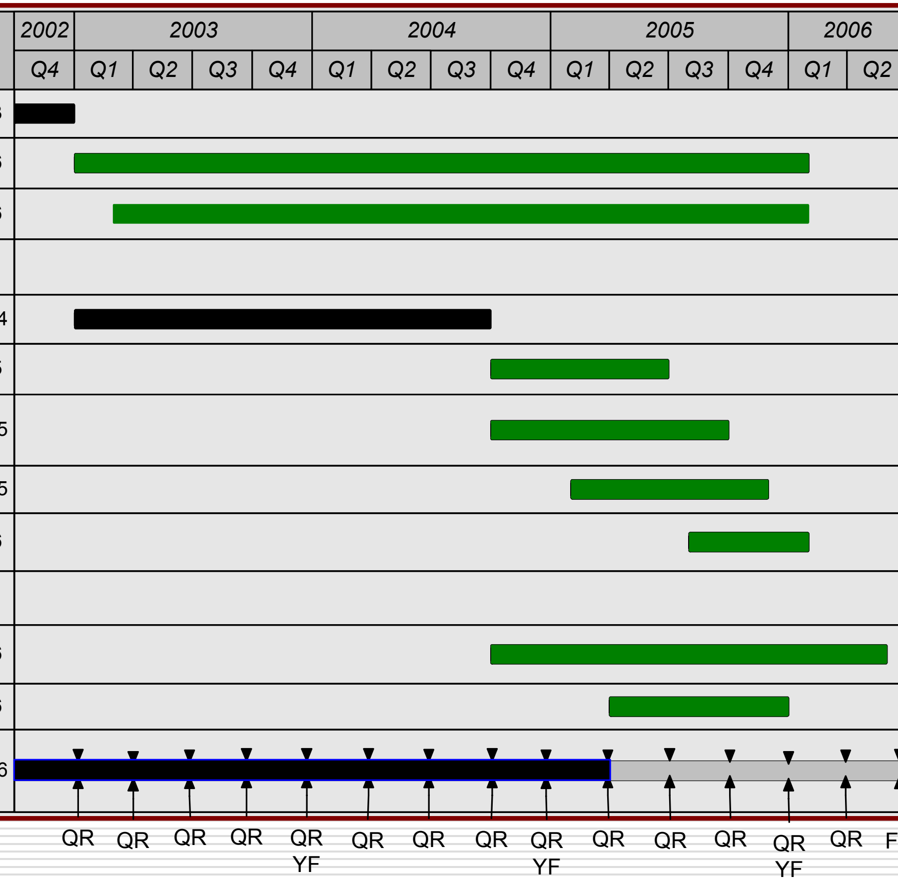
NO_X Emissions Model with Two Adsorbers in Parallel



- Assuming
  - 0.018 g/s engine out emissions without aftertreatment at steady state
  - 90% adsorber efficiency, 50% engine decomposition percentage
- Overall NOx reduction is 82%
- Higher decomposition percentage allows downsizing of the adsorption system

Timeline

ID	Task Name	Start	Finish
1	**Task 1 - Preparation of milestone plan**	10/1/2002	1/1/2003
2	**Task 2 - NOx adsorbtion**	1/1/2003	2/1/2006
3	**Task 3 - NOx desorbtion**	3/1/2003	2/1/2006
4	**Task 4 - NOx decompostion**		
5	4a) Experimental work phase I	1/1/2003	10/1/2004
6	4b) Chemical kinetic modeling	10/1/2004	7/1/2005
7	4c) In-cylinder pressure measurement and experimental work phase II	10/1/2004	10/1/2005
8	4d) EGR, Stoichiometric operation	2/1/2005	12/1/2005
9	**Task 5 - NOx loading (measurement)**	8/1/2005	2/1/2006
10	**Task 6 - Optimize system configuration**		
11	6a) Overall system model and validate for a large bore natural gas engine	10/1/2004	6/1/2006
12	6b) Economic feasibility	4/1/2005	1/1/2006
13	**Task 7 - Project management, reporting & education**	10/1/2002	6/30/2006



Completed tasks

In progress

QR - Quarterly reports due
YF - Yearly report due
FG - Final report due

Future Plans

- Additional EGR/Stoichiometric runs, cylinder to cylinder variation, effect of EGR
- Chemical kinetic modeling - effect of exact EGR quantity
- NOx adsorption/desorption – determine loading rates as a function of temperature
- System modeling – two adsorbers – possible desorption loop – system sizing
- Economic analysis – capital and operating costs
- Propose (and possibly validate) large bore engine application

Cooperative Research

- Request engine manufacturers to review control scheme
- Request Sorbent Technologies to review economic analysis
- Work with Colorado State University on large bore application

Graduate Students

- Matt Swartz – graduated, May 05
- Ramprabhu Vellaisamy – graduated, May 05
- Chamila Tissera – expected graduation, Sep 06
- Emre Tatli – expected graduation, May 07
- Andy Zimmerman – expected graduation, May 06

- Publications/Presentations
  - SAE 2005-01-0234
  - ASME ICED2004-839
  - Second Annual Advanced Stationary Reciprocating Engines Conference
  - ORNL Workshop